

Microphysical Characteristics of Tropical Clouds

Final Technical Report

NASA Contract No. NAG5-9656

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Introduction.

This report summarizes the work done under NASA contract No. NAG5-9656. This work dealt with the analysis of data collected by the University of North Dakota Citation II measurement platform during three TRMM Field measurement campaigns. The Citation II made cloud measurements during TEFLUN B in Florida, the LBA program in Brazil, and KWAJEX in Kwajalein.

The work performed can be divided into two parts. The first part consisted of reformatting the Citation data into a form more easily used to compare to the satellite information. The second part consisted of examination of the cloud data in order to characterize the properties of the tropical clouds. The reformatting of the Citation data was quite labor intensive and, due to the fact that the aircraft was involved in three of the field campaigns, it required a substantial number of person-hours to complete. Much of the analysis done on the second part was done in conjunction with the thesis work of Nicholas Anderson, then a graduate student at the University of North Dakota.

Formatting of the Citation Data.

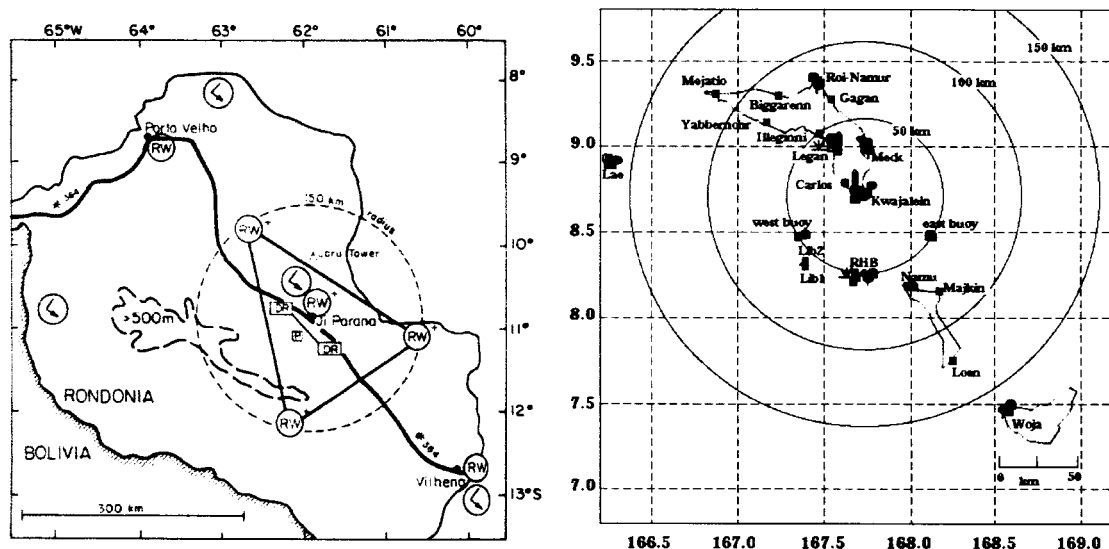
The cloud microphysics data collected by the aircraft can be processed in a number of ways. There are various methods of calculating the size spectra of the cloud particles. Most approaches use some sort of artifact rejection scheme to account for particles that may break upon impact with the probes, melting of accumulated ice on the probes when flying through supercooled water, corrections for the finite rise or fall times of the photodiodes, etc. A number of discussions were held with personnel from NCAR and other involved institutions in order to get a consistent means of processing the cloud image data. Finally, a Common Microphysics Product Definition (CMPD) was derived for the reprocessing of the cloud microphysics data.

The CMPD represented a substantial variation from the normal products produced from the Citation data sets. A description of the CMPD can be found at the web site <http://www.atmos.washington.edu/kwajex/ops-web/prioritylegs/CMPD.rel4.pdf>. The aircraft data were then put into flight legs that were determined to be of high priority and the data were broken into individual 1 km flight segments for each leg. A description of this Common Flight Product Definition (CFPD) can be found at the web site <http://www.atmos.washington.edu/kwajex/ops-web/prioritylegs/CFPD.rel4.pdf>.

There were priority legs defined that were of particular interest for satellite intercomparisons. The data for these flights were put into the format described and are resident on the DAAC sites. There were 21 legs for the TEFLUNB field program, 52 legs for the TRMM LBA field program, and 323 legs for the KWAJEX field program.

Analyses of the TRMM Cloud Data.

The data used in this portion of the study were primarily from the LBA and KWAJEX field programs. These areas are shown in Figs. 1 and 2, respectively.



Figs. 1 and 2: Experiment maps for TRMM-LBA and KWAJEX. Figures from the LBA science overview and the NASA DAAC website, respectively.

Both of these projects included a vast amount of instrumentation that sampled many parameters of the environment. TRMM-LBA and KWAJEX had multiple radars, soundings, and surface observations. Also, both projects had in-situ measurements of cloud microphysics from research aircraft. This study focuses on the data collected in both projects from the University of North Dakota's Cessna Citation II aircraft. In particular, this paper will examine updraft cores in tropical clouds and their characteristics, including strength, size and composition.

The common definition of an updraft core was introduced in 1980 when LeMone and Zipser published two papers (LeMone and Zipser 1980, Zipser and LeMone 1980) on vertical velocity events during the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE). In their analysis, updraft cores were required to have a vertical velocity of 1 m/s or more for a length of at least 500 m. For many research aircraft, including the Citation, 500 m corresponds to approximately 4-5 seconds of flight time.

There have been several studies which have dealt with tropical convection since the GATE papers. Some of these studies have been based upon direct aircraft observation, while others have used data from remote sensing technology. Most of the studies using aircraft observations have analyzed updraft cores in the same manner as

LeMone and Zipser, making comparisons easy. The results from these studies point to tropical updrafts being weaker than midlatitude continental updrafts.

In this paper, the data from LBA and KWAJEX will be compared to each other to examine the differences between tropical oceanic and tropical continental convection. The LBA and KWAJEX data will also be compared to the previous studies about updraft characteristics in both tropical and midlatitude areas. Then, using parcel theory, an attempt will be made to explain the weak nature of tropical updrafts.

DATA

The Citation was used to collect microphysical data in a number of different situations for the TRMM support missions. Flights were flown specifically for stratiform precipitation, convection, precipitation and ice initialization, and coordination with other instrumentation (profiler, balloons, etc). Due to the number of flights of different types, the Citation sampled a wide assortment of clouds and updrafts. Therefore, the data described in this paper represents no one particular type of convection. An updraft core fitting the proper definition was included in this study without being further separated into categories (e.g. cloud age, organized vs isolated convection, etc.).

a) Flight Legs

The Citation was joined by NASA's ER-2 for the TRMM-LBA project. The ER-2 is a high altitude research aircraft, so the Citation mainly sampled the middle to upper parts of the clouds, while the ER-2 flew above cloud top. The Citation flew legs that ranged in altitude from 1.0 to 10.7 km, with a majority of the legs between 4.6 and 7.6 km. The Citation flew 20 missions in TRMM-LBA in which there was an updraft

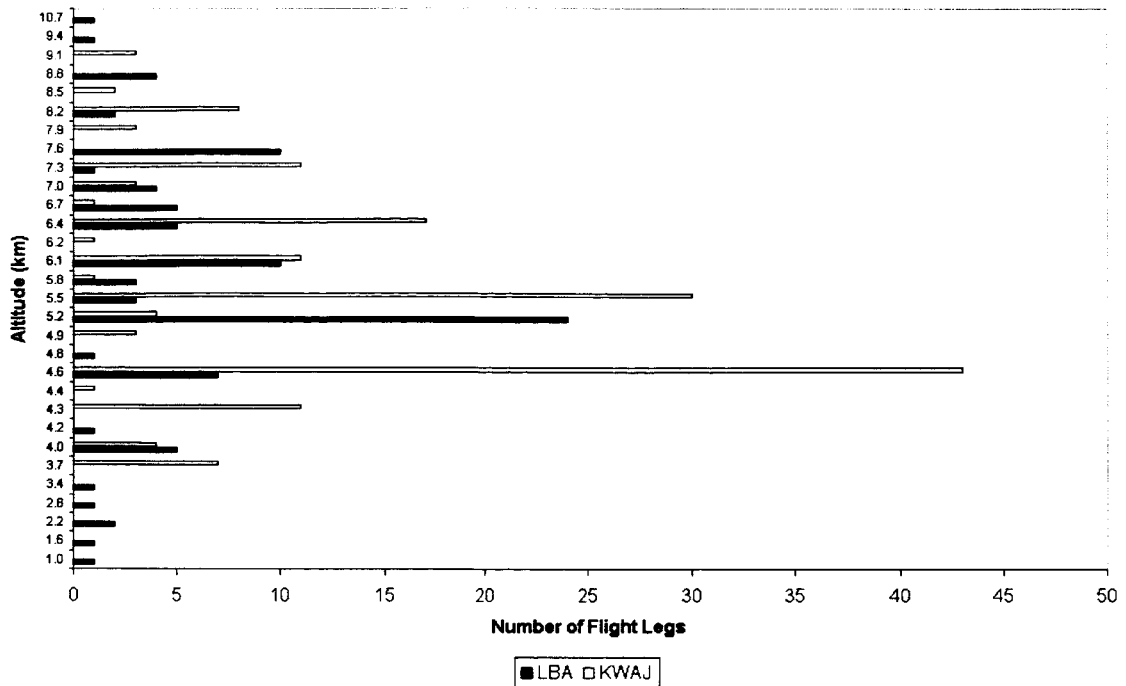


Fig. 3: Distribution of the number of flight legs including updraft cores from TRMM-LBA and KWAJEX.

core recorded. In these 20 missions, there were 293 flight legs flown. Flight legs were defined as straight and level flight. They were selected by analyzing the altitude and heading data. Vertical wind data were omitted due to a sensor error in 23 of those legs. Most of the bad vertical wind data were due to an incorrect attack angle. Of the remaining data, there were around 11,600 km of flight legs to work with. The Citation encountered at least one updraft core meeting the definition described earlier in 93 legs. The total distance of the legs with updrafts was 2,700 km. The distribution of the number of flight legs with updraft cores is shown in Fig. 3, while the total lengths of the legs at each altitude is shown in Fig. 4. The average length of a flight leg in LBA was around 30 km.

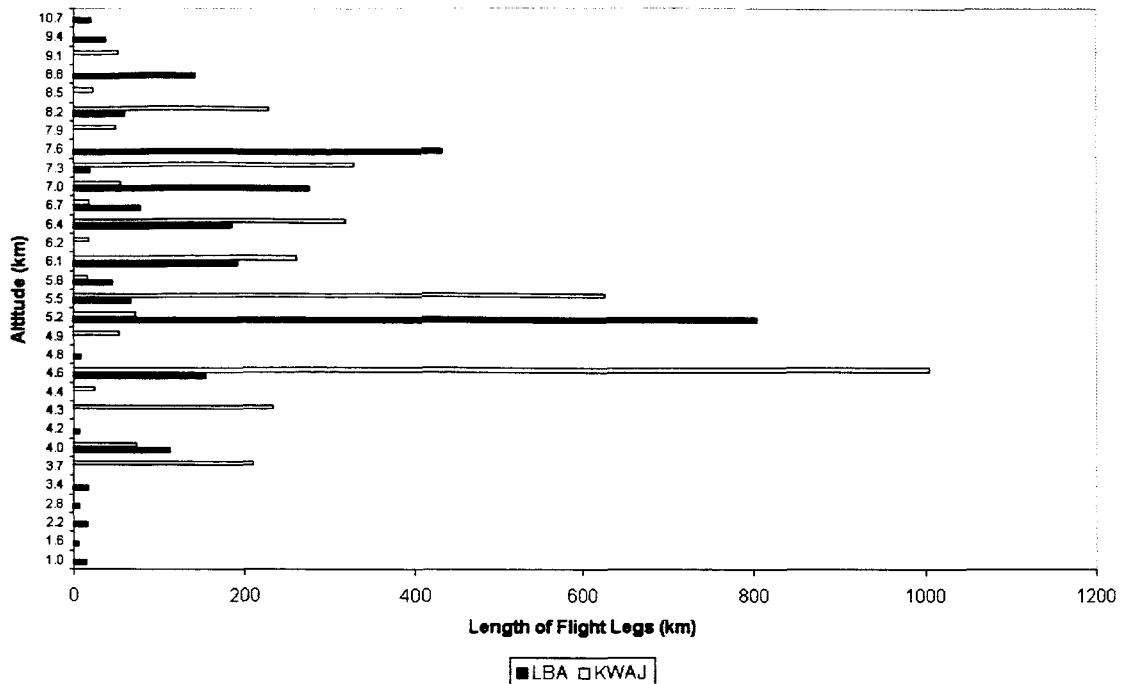


Fig. 4: Total flight leg length per altitude, for legs with updraft cores, from TRMM-LBA and KWAJEX.

The Kwajalein Experiment included three research aircraft. Joining the Citation were the University of Washington's Convair and NASA's DC-8. When all three aircraft were flying, the Convair would take the lower regions of the cloud, the Citation would intercept the middle, and the DC-8 would sample the cloud top and above. If the Citation and the DC-8 were the only aircraft sampling, then the Citation would fly at an altitude of 8 km and lower. When only the Citation and Convair were in the air, the Citation would make cloud penetrations from 6 km to the tops of the clouds. As can be seen in Fig. 3, during KWAJEX the Citation flew legs with altitudes ranging from 3.7 to 9.1 km. The Citation flew 19 missions during KWAJEX that included at least one updraft core. There were 360 flight legs flown, totaling near 8,400 km. Data problems eliminated 73 legs. Of the remaining 6,400 km of flight leg data, there were 164 flight legs that included an updraft core. The total length of these legs was slightly less than 3,700 km. The average length of a flight leg during KWAJEX was 22.3 km.

Flight leg length was one difference between the projects outlined in this paper and the previous studies. The flight legs during LBA and KWAJEX were, on average, shorter than the legs from other studies. This is likely due to the sampling of individual cells as opposed to mesoscale size events. For example, during GATE most of the flight legs were 90-180 km, except when intercepting isolated convection, which had flight legs of around 30 km (LeMone and Zipser 1980). In EMEX, all of the missions were in MCS's, so leg lengths were longer, typically 75 km (Lucas et al. 1994).

Another difference between LBA and KWAJEX and the previous studies were the altitudes of the flight legs. The Citation flew legs that were higher than the other aircraft projects (outlined in Section 4). No flight legs were flown above 8 km in GATE, EMEX, or TAMEX (Jorgensen and LeMone 1989), and most were below 6.5 km.

Therefore, the amount of legs flown above 6 km during LBA and KWAJEX make the Citation data sets unique.

b) Instrumentation

The Citation flew with a suite of instruments. Of particular interest were the liquid water sensors. The CSIRO (King) liquid water probe, the Rosemount icing detector and the forward scattering spectrometer probe (FSSP) were included in both missions. Unfortunately, the King probe and FSSP both had problems in KWAJEX. The FSSP did not work correctly for the first 2/3 of the project, while the King probe only had data for 6 flights. Large graupel was likely the culprit for the King probe failure (Stith et al. 2002). Several different wire elements were broken during the project. For cloud particle measurements the instruments included were Particle Measuring System's (PMS) FSSP-100, 1D-C (KWAJ only), 2D-C, 1D-P (LBA only), and Stratton Park Engineering Company's (SPEC) HVPS and CPI. Temperature measurements were made by the Rosemount probe, which has well-known sensor wetting problems (Jorgensen et al. 1989). Vertical velocity was determined using the equations of Lenschow (1986). The absolute accuracy is around 1 m/s. A thorough description of the instrumentation and calibration techniques for the Citation during LBA and KWAJEX is given by Stith et al. (2002).

c) Updraft core definition

To be considered an updraft core, the vertical velocity must be at least 1 m/s for a flight length of 500 m or longer. There are several other conditions that apply to defining an updraft core. One such condition is that the updraft core must be in the middle of a straight and level flight leg. Thus, only updraft cores in a predefined flight leg with a constant altitude and roll angle of less than 10° were considered. Also, the updraft core had to be less than 7 km across, matching the definition of LeMone and Zipser (1980). The vertical wind data from the flight legs was corrected for any offset from zero. This involved averaging the vertical wind over all flight legs at a certain level each day (Lucas et al, 1994). Any leg with an offset in excess of 1 m/s did not have its data included when identifying the updraft cores. This rarely happened, and it was usually due to sensor error or a large updraft in a very short leg. The correction factors in this study were somewhat higher than in the other studies that used this correction scheme. This is likely due to the shorter flight legs. The last condition was that the cores had to occur in a cloud. The cloud definition used was a FSSP concentration of $10/\text{cm}^3$ or greater or a 2D-C shadow-or concentration of 0.5/L or greater. Shadow-or is the count of any particles that trigger the 2D-C.

RESULTS

The strength, size, and composition of the updraft cores from TRMM-LBA and KWAJEX were determined by analyzing the 1-hz vertical velocity, air speed, altitude, temperature, liquid water and cloud particle data. The results in this section represent the average value over the width of the updraft core, except when noted. The results show that the updraft cores measured during LBA and KWAJEX are similar in strength, but have some differences in size and composition.

a) Updraft core structure

There are four main characteristics of updraft core structure discussed in this section: average updraft core speed, maximum updraft core speed, updraft core width, and mass flux per unit distance. The average updraft core speed is defined as the mean of the one-second vertical velocities over of width of the updraft. The maximum updraft core speed is the peak one-second value. Updraft core width is determined by multiplying the mean flight speed (in m/s) by the number of seconds that the aircraft was in the updraft core. Mass flux per unit transverse distance is defined as

the product of the air density, diameter and mean updraft speed (Lemone and Zipser, 1980). For brevity's sake, it will be referred to simply as mass flux in this paper. The vertical velocity of an updraft is perhaps its most defining characteristic. It controls the cloud's ability to hold precipitation-sized particles, helps define the amount of mass transport possible, and changes the temperature level at which liquid water can be found. Figure 5 shows a histogram of the average updraft core speeds from LBA and KWAJEX. The distributions for maximum updraft core speed, diameter, and mass flux were similar, with a peak at smaller values. Figure 6 shows the distribution of the average updraft core speed with altitude of every core sampled during LBA and KWAJEX. As was shown with the flight leg data, almost all of the updraft cores are within an altitude range of 4.0 to 9.0 km. In order to facilitate comparisons between this and other studies, the data for various parameters is divided into altitude ranges. Care was taken to have a similar number of cores in each altitude range, but not at the expense of separating updraft cores that were only a few meters apart. Table 1 shows the altitude ranges along with the number of updraft cores. There were 215 updraft cores analyzed in LBA and 377 from KWAJEX. Twelve of the LBA cores were not represented in the altitude separation statistics because they were not closely associated with any of the altitude groups (e.g. Fig. 6, cores from 1 to 3 km). After the updraft cores were placed in their altitude categories, the 10, 50, and 90% values for the four main characteristics were calculated. Ten-percent values indicate that 90% of values fall below that number, while the median is represented by the 50% value. The 10% and 50% values will be used in the next section, when LBA and KWAJEX will be compared to other studies.

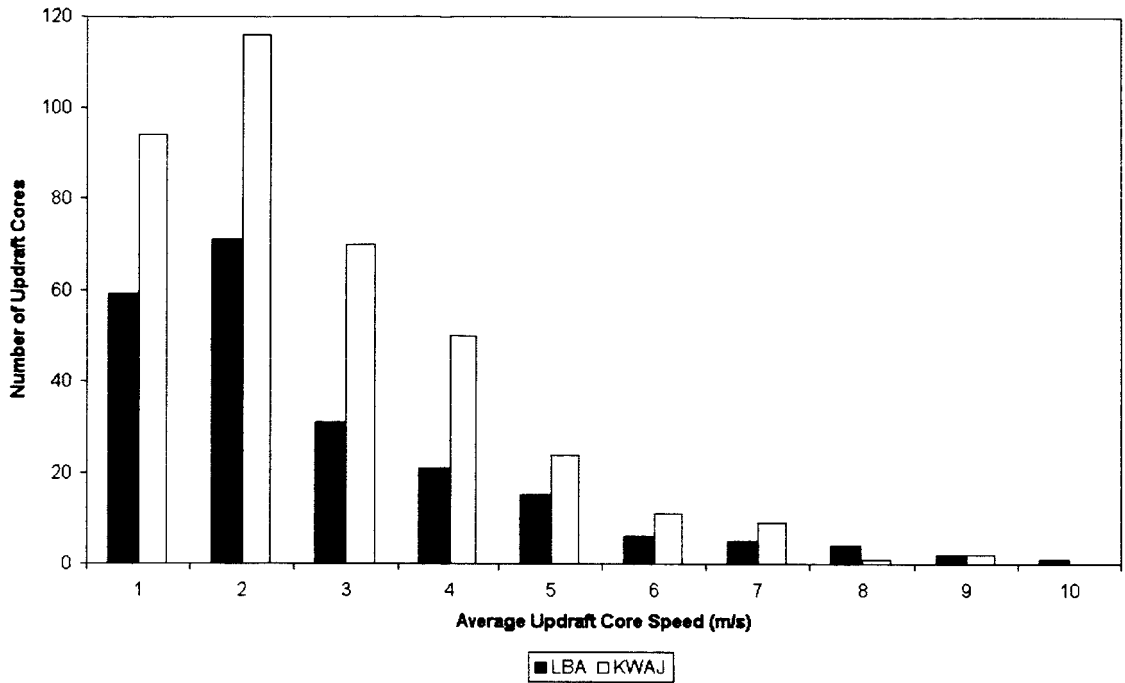


Fig. 5: Histogram of average speeds of updraft cores during LBA and KWAJEX.

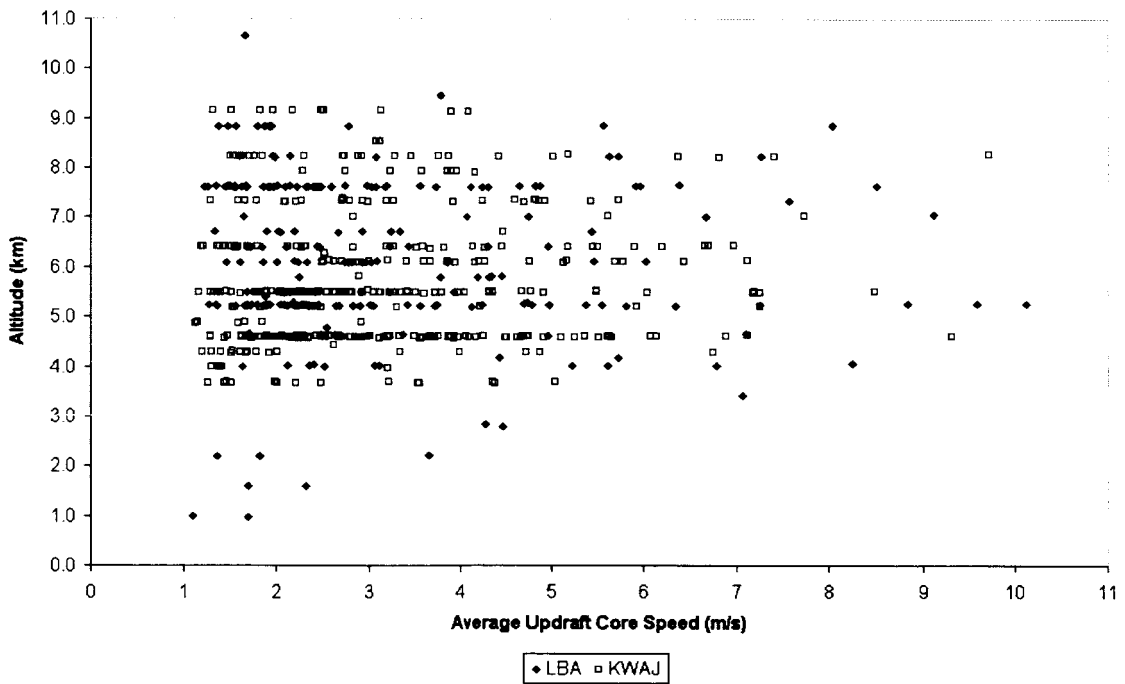


Fig. 6: Average speed of updraft cores sampled during LBA and KWAJEX.

Table 1: Altitude separation for LBA and KWAJEX, and the number of updraft cores in each division.

Height Interval (km)	LBA			KWAJEX			
	3.9-5.2	5.3-7.3	7.5-8.8	3.6-4.6	4.8-5.5	5.8-6.7	7.0-9.1
Number of Cores	79	55	69	144	97	65	71

Table 2 shows the numbers for the median and 10% values from the altitude separation. Taking a look at the average updraft core speeds, we find that the intensity of the cores in LBA and KWAJEX are quite similar. The median values of average updraft core speed for both projects reach a maximum in the 6 to 7 km altitude range. The average updraft core speeds have a median value of 3.2 m/s for KWAJEX and 2.9 m/s

Table 2: Values of selected updraft core characteristics.

Range (km)	Diameter (km)		Average (m/s)		Maximum (m/s)		Mass Flux ($10^3 \text{ kg m}^{-1} \text{ s}^{-1}$)	
	50%	10%	50%	10%	50%	10%	50%	10%
LBA (1999)								
3.9-5.2	0.9	2.0	2.5	5.8	4.1	11.8	1.8	6.2
5.3-7.3	1.0	2.0	2.9	5.4	4.8	9.6	1.7	5.2
7.5-8.8	1.0	2.7	2.2	5.6	3.2	10.2	1.1	4.8
KWAJEX (1999)								
3.6-4.6	0.9	2.7	2.6	4.9	4.1	8.3	1.8	8.0
4.8-5.5	1.2	2.5	2.5	4.8	3.7	8.0	1.9	6.7
5.8-6.7	1.2	2.6	3.2	5.9	5.5	9.9	2.5	10.2
7.0-9.1	1.2	3.3	3.1	5.4	4.9	9.6	2.0	9.1

for LBA at that level. The difference between the two study areas increases in the upper levels. For the 7.5 to 8.8 km range the median average updraft core speed during LBA was 2.2, compared to 3.1 m/s for the 7.0 to 9.1 km range in KWAJEX. The standard deviation of the average updraft core speeds range from 1.5 to 2.0 m/s.

There are two measures of updraft strength: the average value of updraft speed and the maximum value. Figure 7 shows the distribution of the maximum updraft core speed with altitude. The median values of maximum updraft core speed reach a peak around 6.0 km, with LBA at 4.8 m/s and KWAJEX at 5.5 m/s. The 10% values reach a peak at the lowest level for LBA, around 4.5 km, while the peak for KWAJEX is around 6.0 km. The strength differences between the two projects are within the standard deviation, which ranges from 2.5 to 3.6 m/s.

We can compare the average and maximum updraft core speeds by looking at Fig. 8, which shows that there is a linear relationship between the two. For the sake of continuity, from this point forward, any time that updraft core speed is mentioned it will refer to the average value over the width of the core. An additional perspective that Fig. 10 gives is confirmation of LeMone and Zipser's assertion that updrafts do not have a

perfect top-hat profile. A top-hat profile means that the updraft core has a constant speed throughout its horizontal width. If this were the case, the average and maximum values would be the

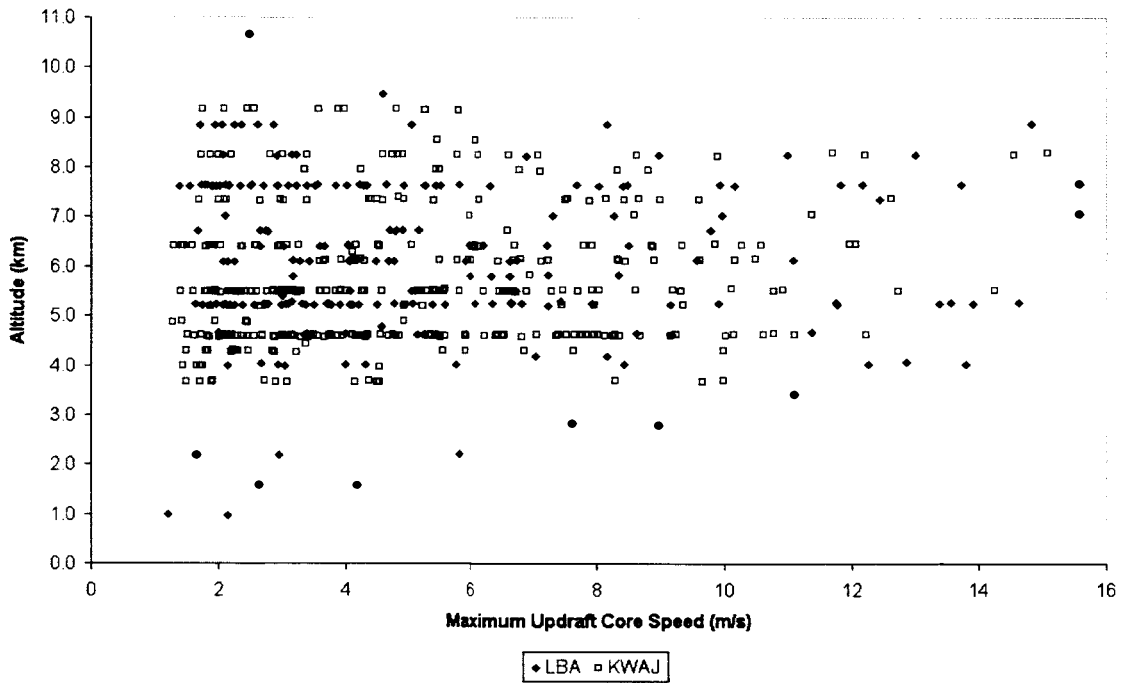


Fig. 7: Maximum speeds for updraft cores from LBA and KWAJEX.

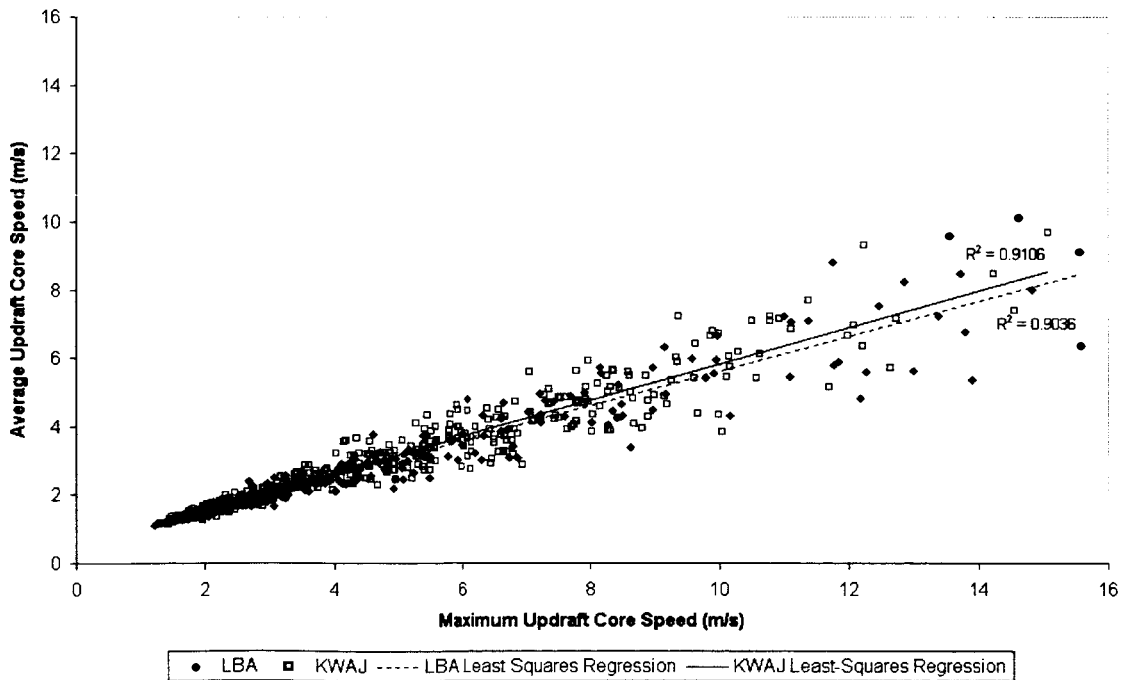


Fig. 8: Maximum vs average updraft core speed for LBA and KWAJEX.

same and Fig. 8 would have a 1:1 ratio, which is not seen at any point. The average updraft core speed for the cores during the two projects was 66% of the maximum value.

Another characteristic of updrafts is their width. Updraft core width versus altitude is shown in Fig. 9. One striking characteristic of this graph is that KWAJEX has the majority of the widest updraft cores. Looking at the median values in Table 3, it is apparent that the LBA cores are slightly smaller, but only above an altitude of 5 km. The 10% values show a wider KWAJEX core by at least 0.5 km at every level. Another important issue is how the updraft core width changes with height. The median values of updraft core width for both LBA and KWAJEX are constant above 5 km. However, the 10% values increase above 5 km.

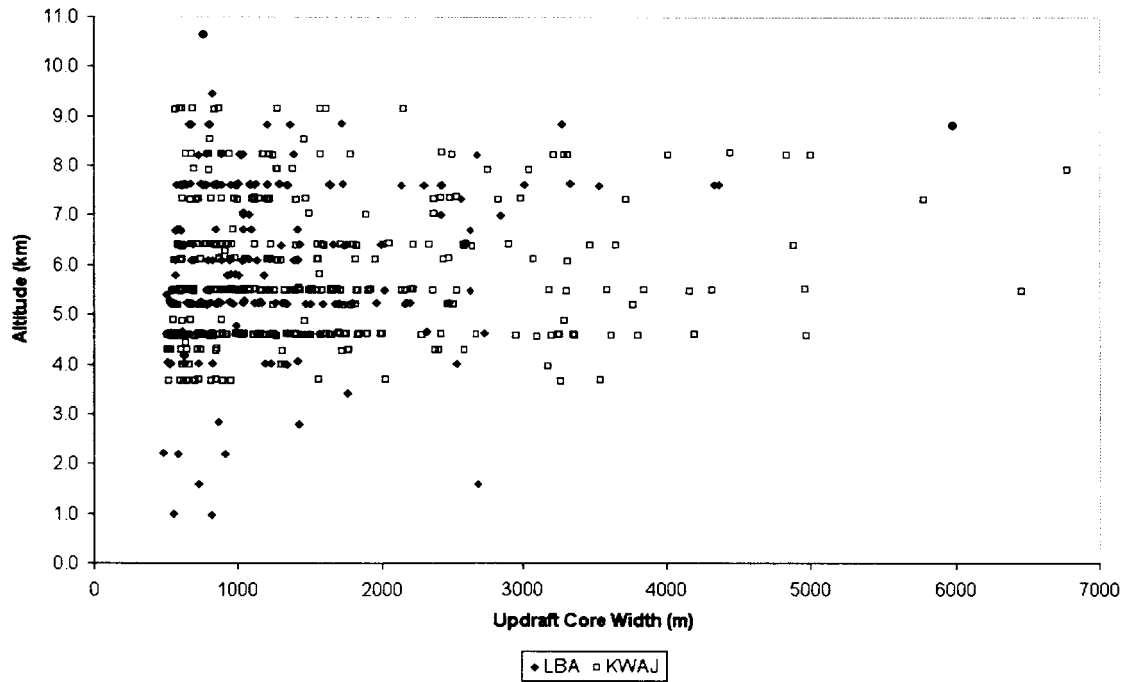


Fig. 9: Updraft core widths for LBA and KWAJEX.

The standard deviation of updraft core width ranges from 0.6 to 1.3 km.

The reason for the interest in updraft core width is that it has been theorized that updraft width and strength are correlated. Entrainment and mixing should reduce the buoyancy of a parcel of air (Lucas et al. 1994), which would decrease the intensity of a rising updraft. Wider updrafts are less susceptible to entrainment and mixing, so they should remain stronger. However, the data from these projects do not strongly support that theory. Figure 10 shows updraft core speed as a function of the width of a core. The positive correlation between updraft width and speed is poor (R^2 values of less than 0.2). Or as Zipser

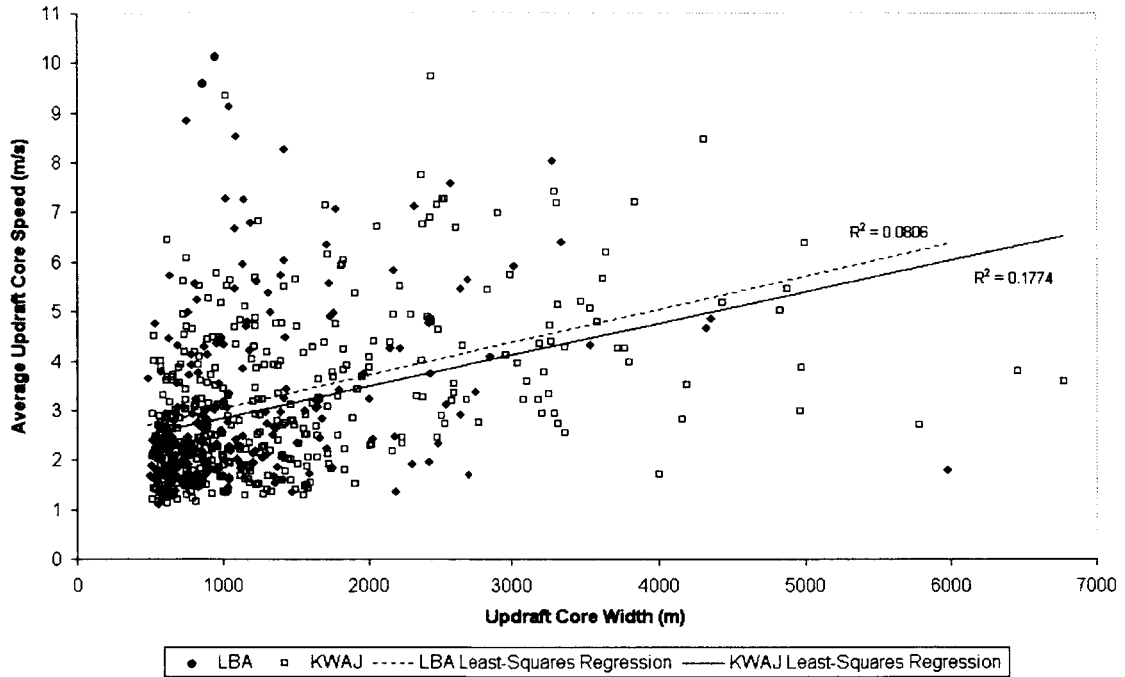


Fig. 10: Comparison between updraft core width and average updraft core speed for LBA and KWAJEX.

and LeMone (1980) said about their daily scatter diagrams relating diameter and vertical velocity: “we succeeded mainly in discovering why they are called scatter diagrams”. Their full data set also showed a very small positive correlation.

Mass flux is another important characteristic of an updraft core. The movement of air within an updraft transports water vapor, aerosols, hydrometeors, etc. Mass flux is important to general circulation modeling because of the requirement for balance within the atmosphere. Mass flux is defined by the speed and width of an updraft, so it would make sense that the distribution of values would be much like that of its components. Indeed, looking at Fig. 11, we find higher mass flux values paralleling the wider updraft cores found during KWAJEX. The median values (Table 2) for both projects are similar below 5.5 km, but then the KWAJEX cores have increasing values above that. This is in contrast to the LBA values which hold steady, then decrease above 7.5 km. The 10% values show an even more dramatic difference, with the KWAJEX cores above 5.8 km approaching double the values of the LBA cores. The standard deviation for LBA ranges from 2.0 to 2.8 $\text{kg m}^{-1} \text{s}^{-1}$, while for KWAJEX it ranges from 3.2 to 4.3 $\text{kg m}^{-1} \text{s}^{-1}$.

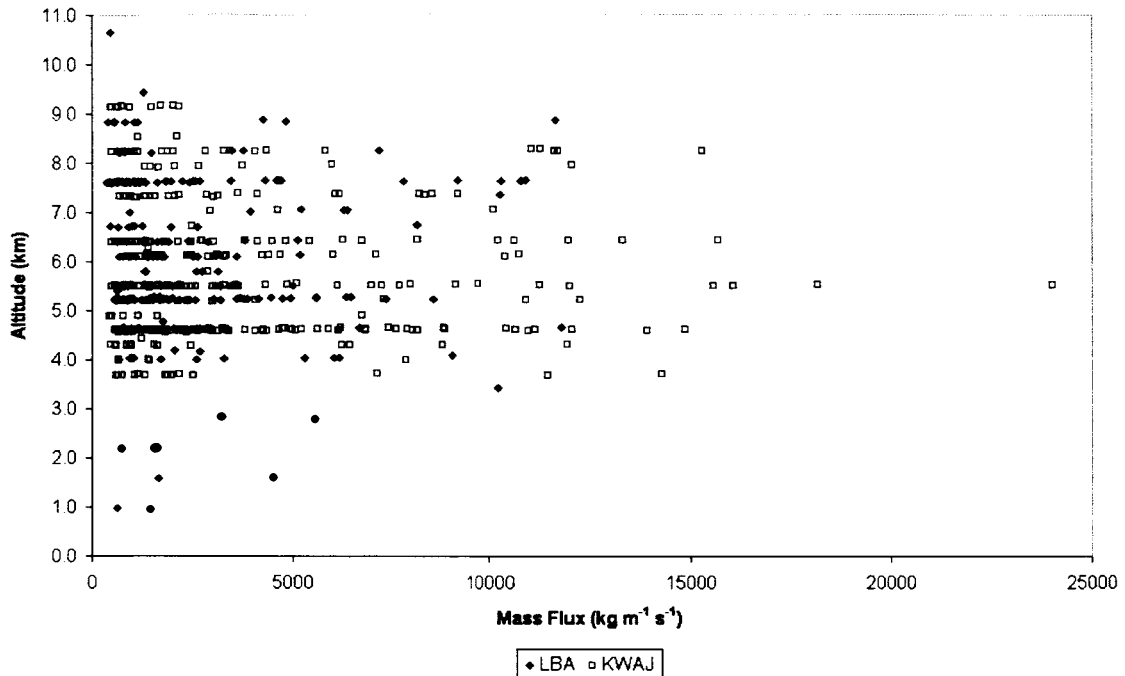


Fig. 11: Mass flux values for the updraft cores sampled during LBA and KWAJEX.

b) Updraft composition

We will now consider the composition of the updraft cores. As was outlined in the previous section, the Citation came equipped with a number of different cloud physics instruments. These instruments allowed us to get an indication of the water content and cloud particle concentrations that were found in the updraft cores.

One of the important liquid water probes was the King probe. Figure 12 shows the distribution of the liquid water content values measured by the King probe. Obviously, there is decrease in the liquid water above the melting level (4.6 – 4.9 km) due to glaciation. There are fewer liquid water content observations from the King probe in KWAJEX, due to the problems outlined in the previous section. However, even with the lack of observations, the peak liquid water contents during KWAJEX were significantly lower than those of LBA. The FSSP indicated liquid water contents similar to that of the King probe during LBA for liquid cases. Table 3 shows the number of cores with liquid water contents above 0.25, 0.5, 0.75, and 1.0 g/m^3 for each of the projects. Warm and cold cases were based solely on the altitude of the cores. An altitude of 5.9 km (with temperatures near -7°C) was found to be reasonably representative of the division between ice and liquid cases. However, not all cases which are defined as cold may be all ice, and not all cases which are warm may be all liquid. For the warm cases, 24% of the observations in LBA had liquid water contents above 0.75 g/m^3 , whereas there were no updraft cores with at least that value in KWAJEX. The discrepancy is not as pronounced when the liquid water content limit is lowered to 0.25 g/m^3 . In that situation, 82% of the cases from LBA are included, as opposed to 63% from KWAJEX.

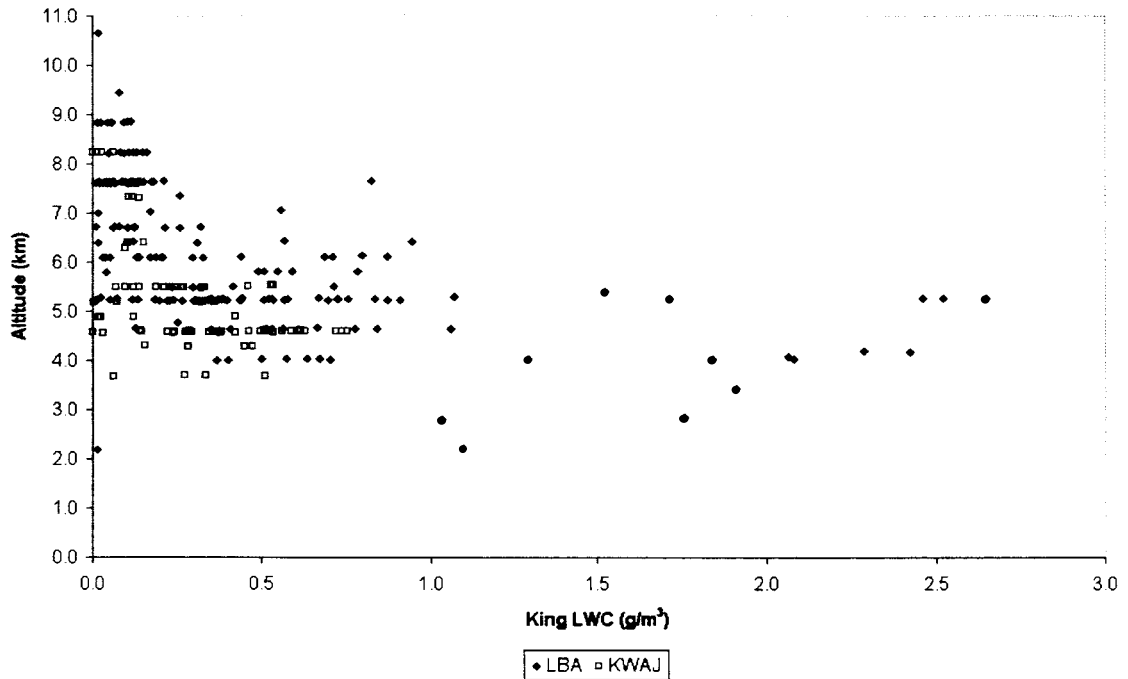


Fig. 12: Liquid water content from the King probe, for LBA and KWAJEX.

Table 3: King liquid water content values during LBA and KWAJEX. Warm cases refer to cores below 5.9 km.

	<u>LBA</u>				<u>KWAJEX</u>			
	Warm		Cold		Warm		Cold	
	#	%	#	%	#	%	#	%
Total Number of Observations	98		109		63		12	
King LWC > 1.0 g/m ³	17	17	0	0	0	0	0	0
King LWC > 0.75 g/m ³	24	24	4	4	0	0	0	0
King LWC > 0.50 g/m ³	47	48	8	7	17	27	0	0
King LWC > 0.25 g/m ³	80	82	15	14	40	63	0	0

In the cold cases, 14% of the LBA cores have a liquid water content of greater than 0.25 g/m³ while KWAJEX had none. The sample size for the cold cases during KWAJEX is very small (only 12 observations, as opposed to 109 in LBA), due to the wire element of the King probe being broken several times in trips above the melting level.

This indicates a major difference between the tropical oceanic updraft cores of KWAJEX and the tropical continental updraft cores of LBA. Oceanic updraft cores may not have as much liquid water because they form precipitation-sized particles more quickly. When the precipitation falls out, the updraft core is left with less liquid water. Zipser (1994) showed that 90% of the updraft cores from GATE, EMEX, TAMEX and atlantic hurricanes would not be able to hold a 1 mm raindrop aloft. The same would be true for LBA and KWAJEX because the 10% average updraft core speeds are similar to those studies (to be shown in Section 4). The influence of the weak updraft core speeds was seen by Jorgensen and LeMone (1989) during TAMEX when they found that updraft

cores had five times the amount of cloud liquid water content, but an order of magnitude less rainwater content than downdraft cores. Median volume diameters (MVD) of droplets measured by the 2D-C probe were analyzed for several flights in LBA and KWAJEX. The MVDs for droplets in LBA cores ranged from 249 to 325 μm , while the KWAJEX droplets were larger, ranging from 348 to 434 μm . This could indicate that the KWAJEX clouds did indeed form precipitation-sized droplets more quickly.

Another scenario that could lead to the lower liquid water content readings in KWAJEX would be a bias in the instrumentation. In this case it could be an underestimation of the liquid water content due to the droplets being too large. According to Biter et al. (1987), the King probe has only a 50% response when the mean volume diameter of the droplets is about 150-200 microns. With the MVDs of the droplets in LBA and KWAJEX even larger than that, the underestimation could have been significant, and would have affected KWAJEX more than LBA.

The King probe was not the only liquid water content measuring probe that the Citation carried during the projects. The FSSP was available for all of LBA and the last six flights of KWAJEX. Unfortunately, it was never working at the same time as the King probe during KWAJEX, so no comparisons can be made there. However, both instruments

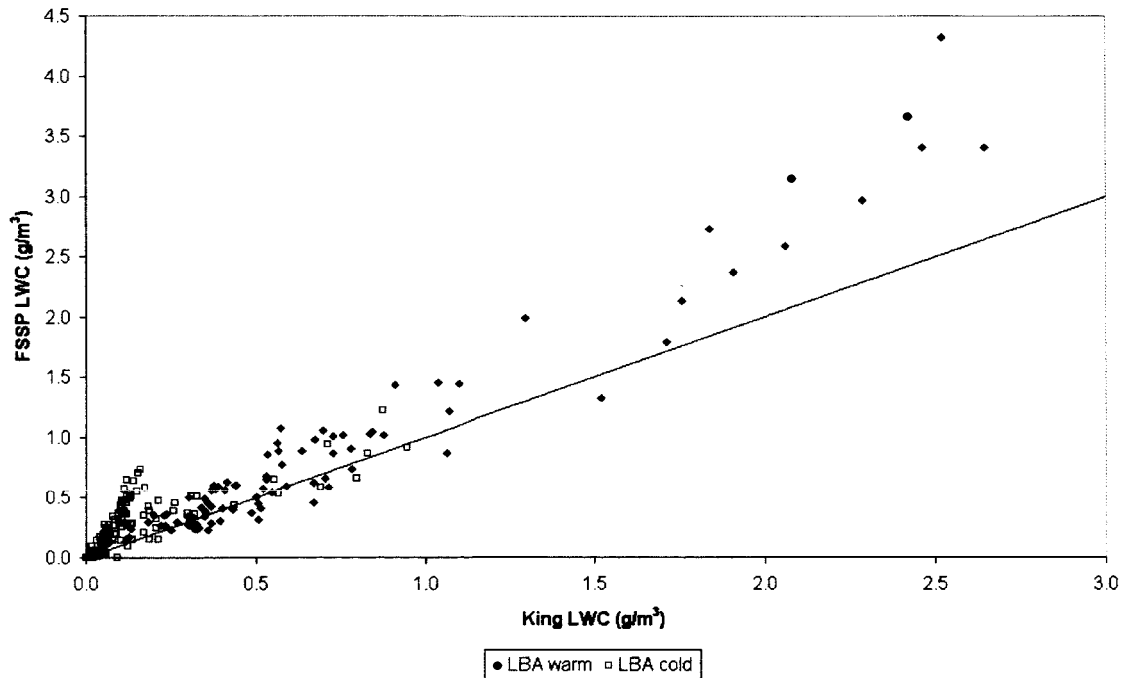


Fig. 13: Comparison of liquid water content measured by the FSSP and King probes. All data is from LBA. The cases are divided into warm and cold (below or above 5.9 km). A 1:1 line is also shown.

worked during LBA. Figure 13 shows the liquid water contents from each probe. The cases were divided up into warm and cold because it is known that the FSSP overestimates liquid water content in the presence of nonspherical ice particles (Gayet et al. 1996). We can see that the warm case readings from the two probes compare favorably to one another, with a slight bias high for the FSSP. For the cold cases, the FSSP read much higher, which was expected.

To determine what contributes to the differences between the FSSP and the King probe, we can look at how they react during periods of different particle concentrations. Figure 14 shows the difference between the two liquid water probes compared to the output from the 1D-P probe. The

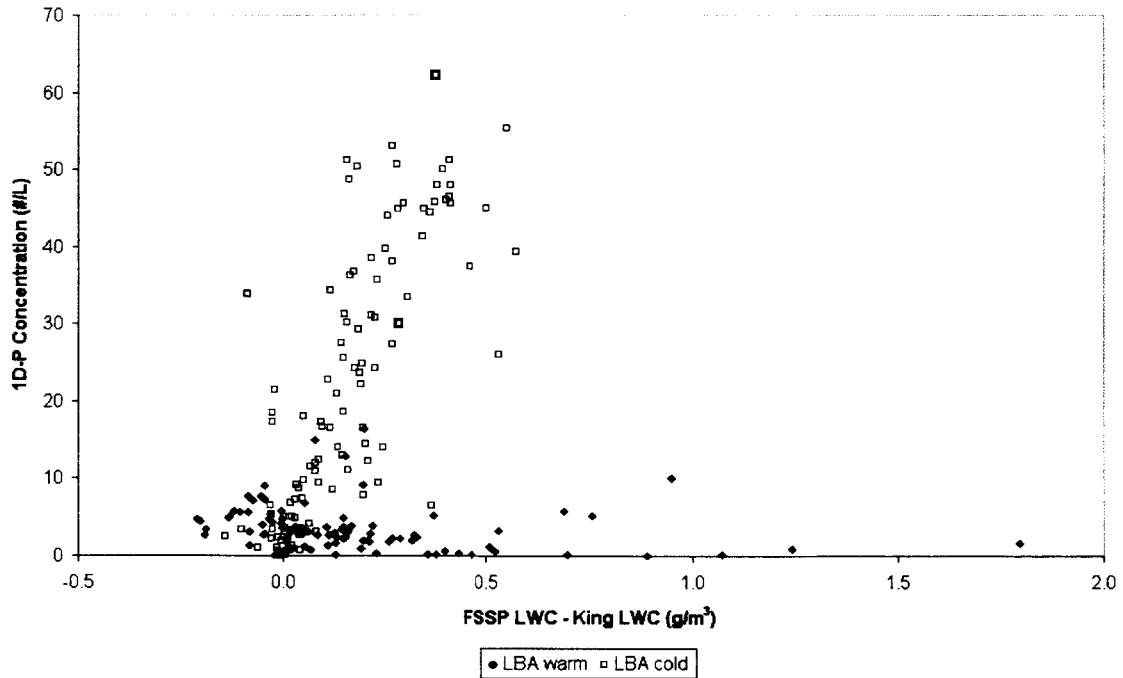


Fig. 14: Comparison of FSSP and King LWC for different concentrations of 1D-P particles. LBA only.

difference between the probes is defined as the FSSP liquid water content minus the King liquid water content. The 1D-P samples precipitation-sized particles. The warm cases have low 1D-P concentrations, and no distinct pattern evolves. The cold cases have many more particles, which can likely be attributed to larger ice crystals. The increased number of large ice particles leads to higher FSSP liquid water contents. The 2D-C shadow-or concentrations (Fig.15) show a similar pattern for cold cases, with higher values from the FSSP. Interestingly, some of the warm cases show an opposite relationship, where higher 2D-C concentrations are associated with King probe values in excess of the FSSP values. This could be due to the FSSP missing the larger cloud droplets that are out of its size range. The FSSP

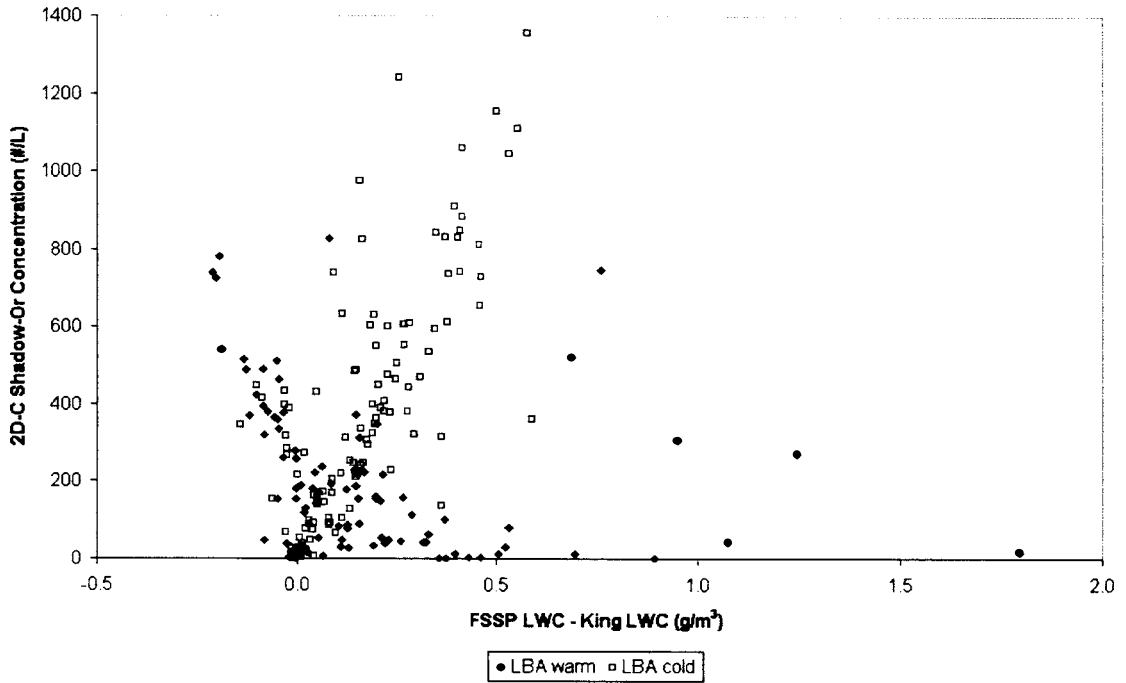


Fig. 15: Comparison of FSSP and King LWC for different concentrations of 2D-C shadow-or particles. LBA only.

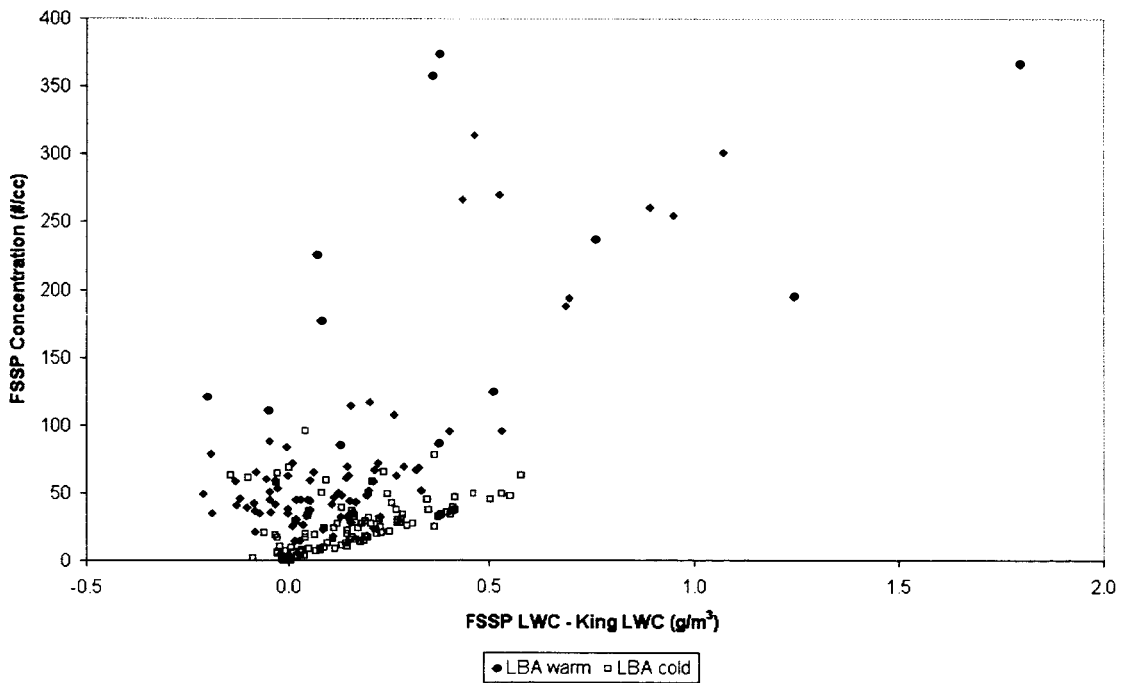


Fig. 16: Comparison of FSSP and King LWC for different concentrations of FSSP particles. LBA only.

concentrations are given in Fig. 16. The cold cases show a pronounced difference between the FSSP and King probe. Again, this is likely due to the FSSP's overestimation of liquid water content with ice present.

In summary, it is obvious that the FSSP is affected by ice particles. This result, plus the questionable FSSP data from KWAJEX, lead to the conclusion that the King probe should give the more accurate estimation of liquid water content, and that is what has been used in this paper.

Figure 17 shows a positive correlation between liquid water content and updraft core strength for LBA and KWAJEX (R^2 values of 0.36 for LBA and 0.41 for KWAJEX). While most of the values for KWAJEX were at lower altitudes where the hydrometeors were liquid, many of the LBA values occurred in

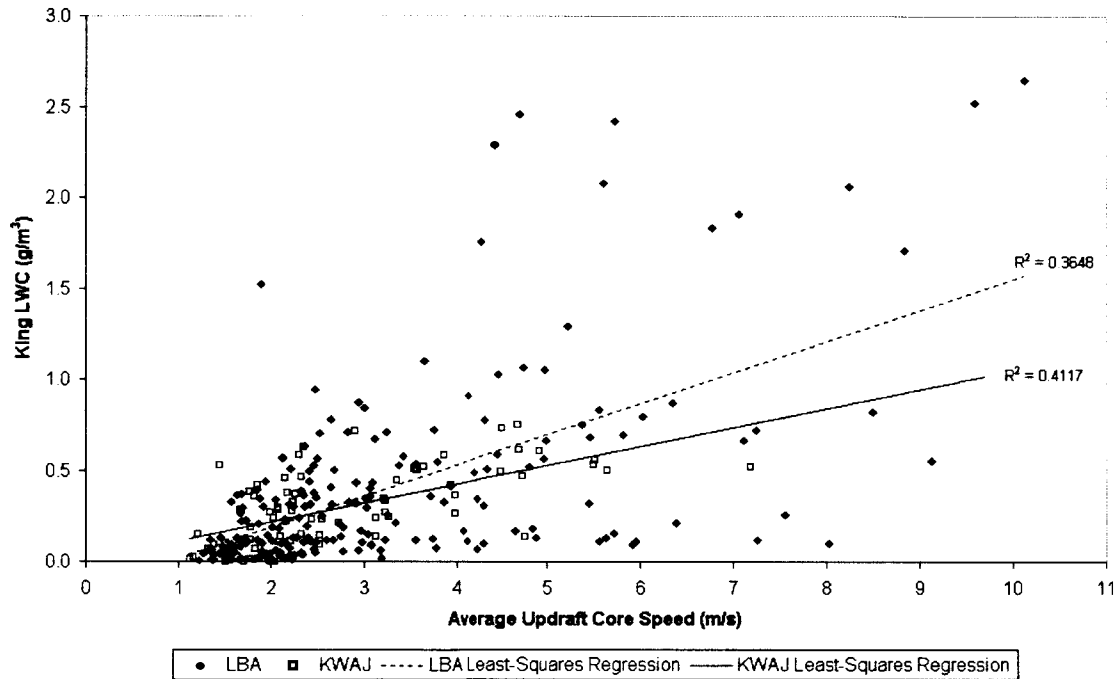


Fig. 17: Average updraft core speed vs King liquid water content for LBA and KWAJEX.

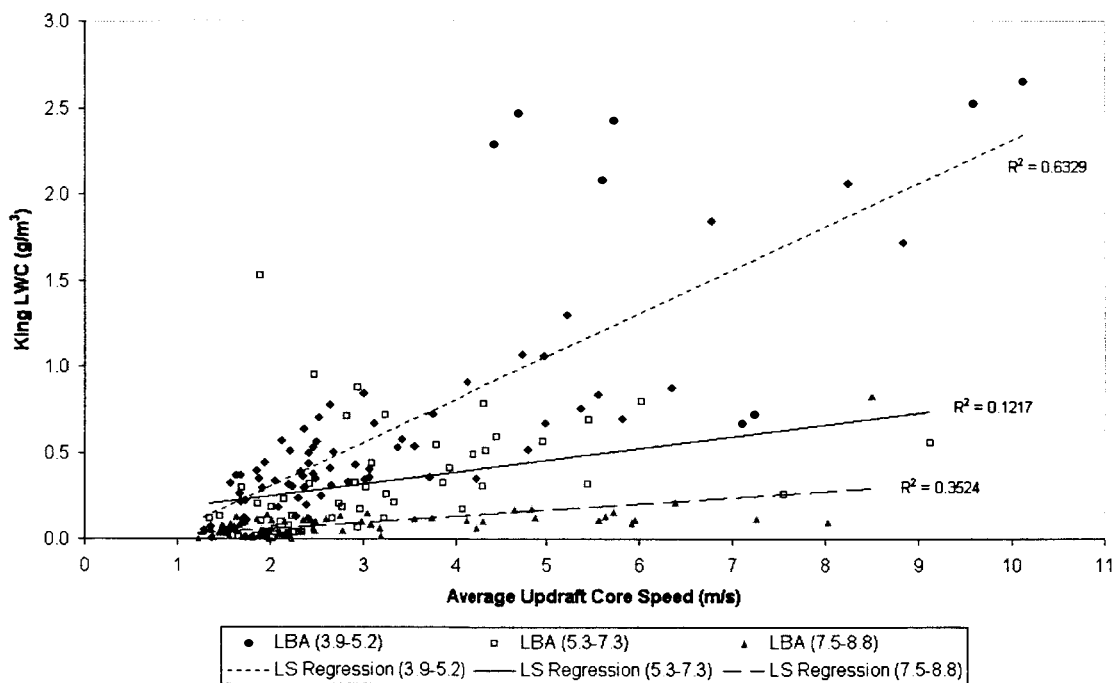


Fig. 18: Average updraft core speed vs King liquid water content for the different altitude categories from LBA.

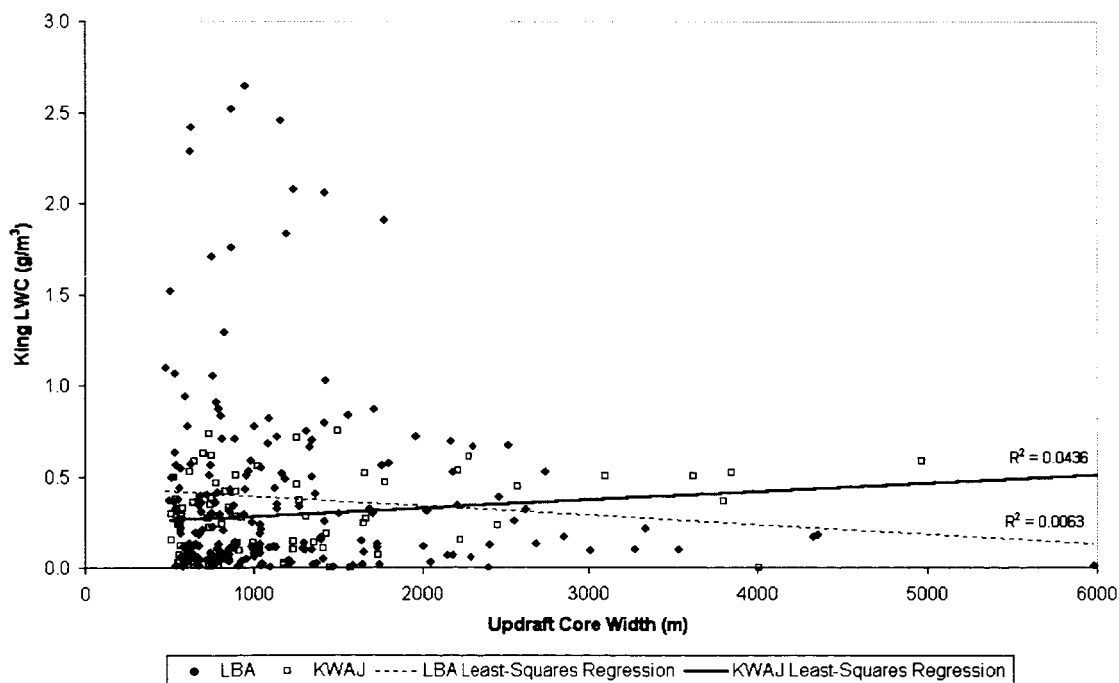


Fig. 19: Updraft core width versus liquid water content from the King probe. mixed-phase or glaciated parts of the cloud. Figure 18 shows the King data from LBA after the cores are separated into the three altitude categories. The correlation improves at the lower altitudes where the droplets are likely liquid (R^2 value of 0.63).

The relationship between updraft core width and liquid water content is very weak (Fig. 19). The highest liquid water contents come from LBA and are all in updraft cores narrower than 2 km. Overall, there is not much of a pattern, with correlation coefficients less than 0.05. This is in contrast to the expectation that wider updraft cores would have higher liquid water contents because the effects of entrainment and mixing would tend to be less.

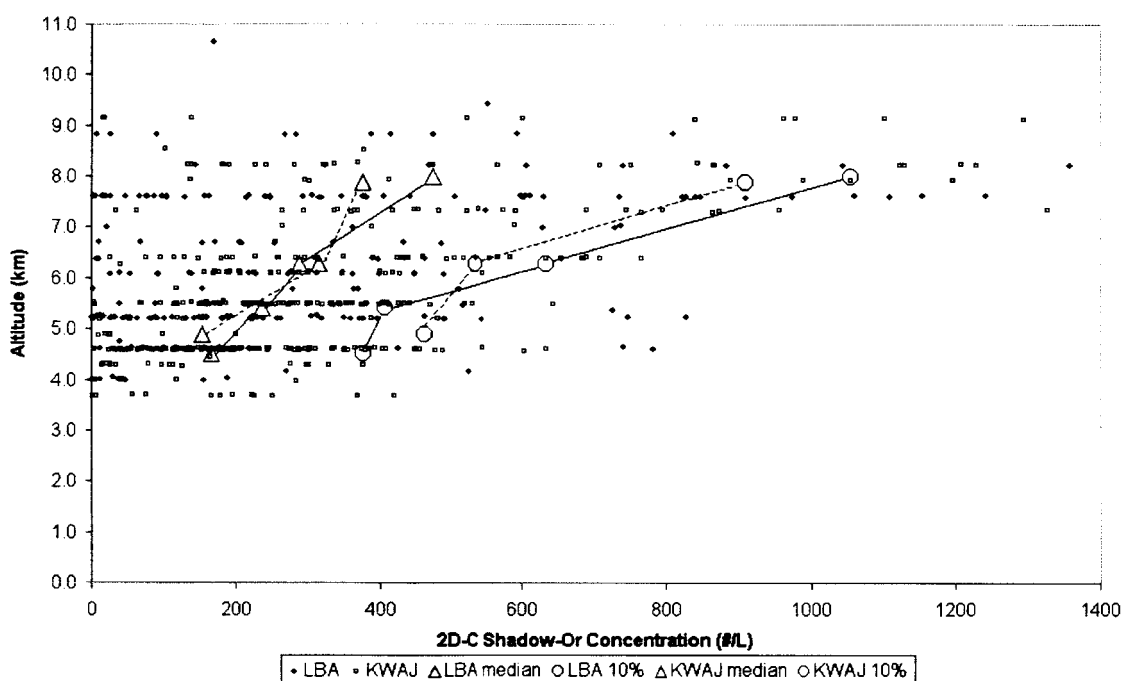


Fig. 20: 2D-C shadow-or concentrations from LBA and KWAJEX and the median and 10% values.

Along with liquid water content, particle concentrations are a major characteristic of clouds and updrafts. The 2D-C probe recorded data for all of the updraft cores identified from both projects. The data used here will be the shadow-or concentrations. Figure 20 shows

the concentration versus altitude. There are significantly more particles at the upper altitudes in both projects. Stith et al. (2002) attributed the increase to secondary ice production methods. The amounts of particles in LBA and KWAJEX updraft cores were nearly the same. The data was separated into the updraft categories and compared (Fig. 20). The median values at the lower altitudes were around 200 per liter, increasing to 400/L around 8 km. The KWAJEX numbers were very slightly higher. The 10% values increased from around 400/L to 1000/L, with similar concentrations for both projects. At first glance this seems counterintuitive because particle concentrations are usually higher over continental areas. However, in LBA, which was held during the wet season, CCN concentrations were low and they resembled marine conditions (Roberts et al., 2003).

As with liquid water content, the particle concentrations from the 2D-C are compared to updraft core strength and width (Figs. 21 and 22). Little correlation was found for either comparison using the full data sets. An improved correlation was found when the droplets were all liquid, as was also shown by Igau et al. (1999) using the data from TOGA COARE. In TOGA COARE, there was a positive

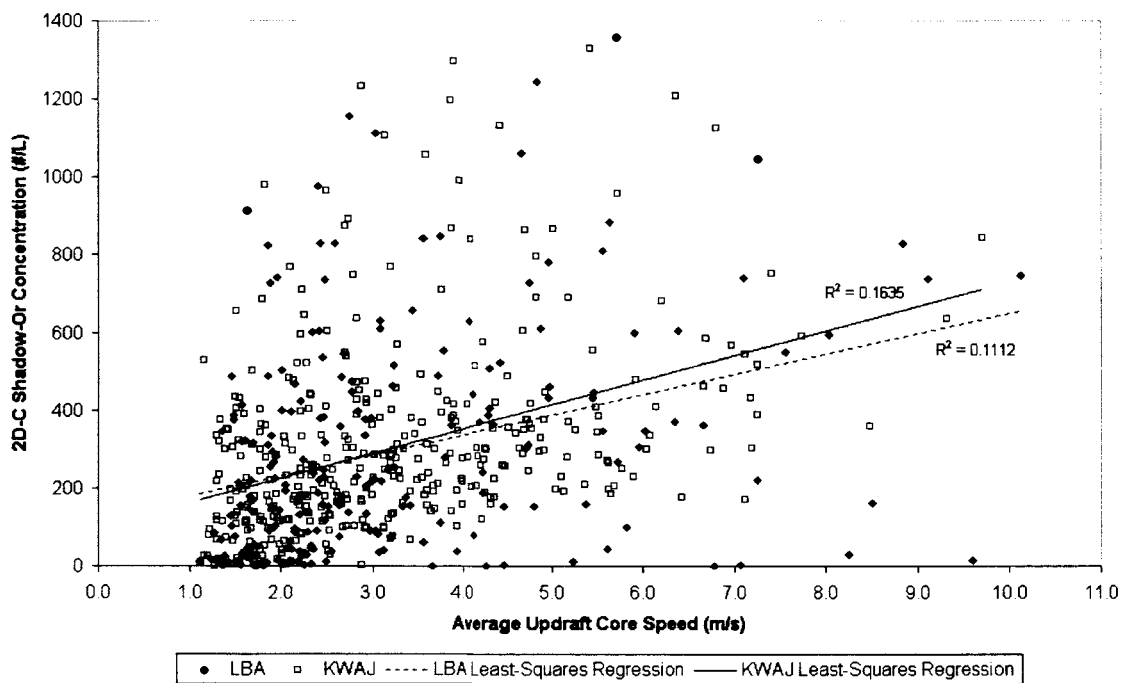


Fig. 21: Comparison between updraft core strength and 2D-C shadow-or concentration.

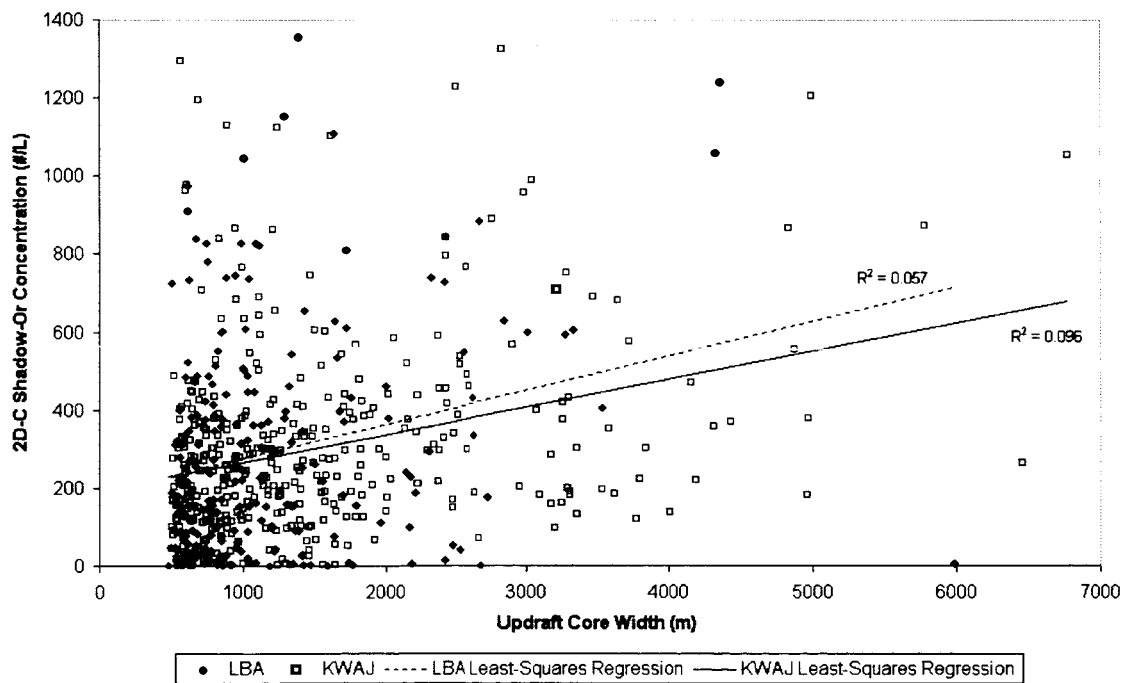


Fig. 22: Comparison between updraft core width and 2D-C shadow-or concentration.

correlation between average updraft core speed and 2D-C concentration ($R=0.50$) for cores from 2.5 to 4.3 km. In KWAJEX the R^2 value was 0.50 for cores from 3.6 to 4.6 km.

The 1D-P probe was only available for LBA, so no comparisons can be made between the two projects. However, the distribution of precipitation-sized particles with altitude (Fig. 23) is interesting. The concentrations very clearly increase above the melting level. This is likely due to the probe sampling large ice crystals and aggregates of ice crystals (Fig. 24). Another thing that the 1D-P tells us is that there are not many raindrops in the updraft cores, as was discussed earlier.

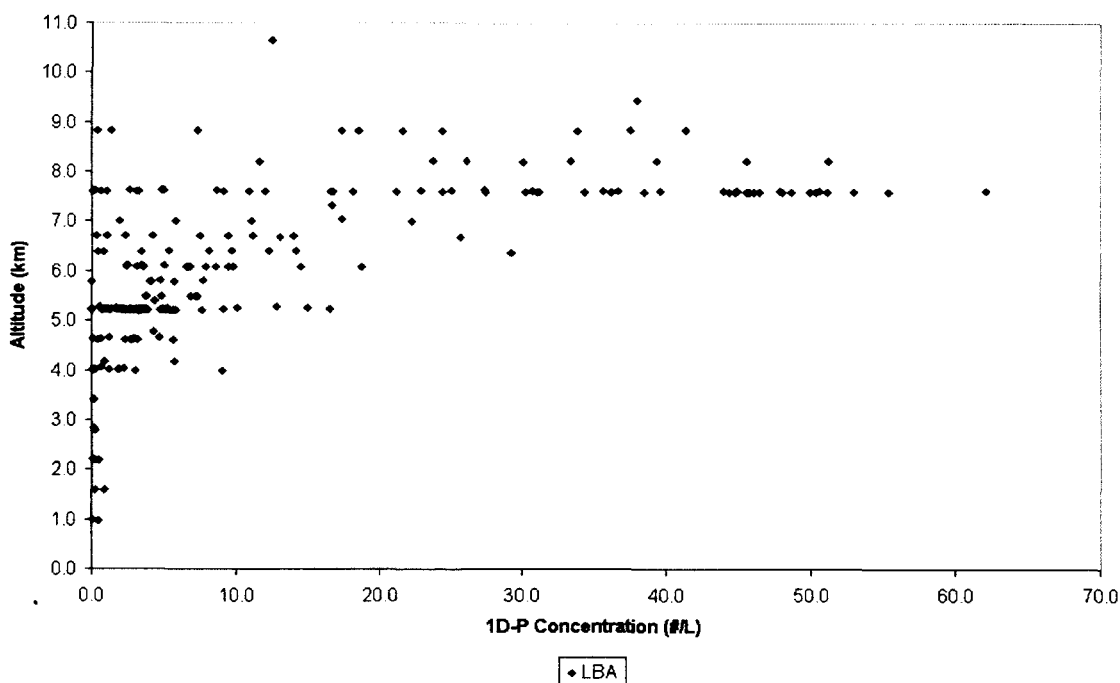


Fig. 23: Particle concentrations from the 1D-P probe. LBA only.

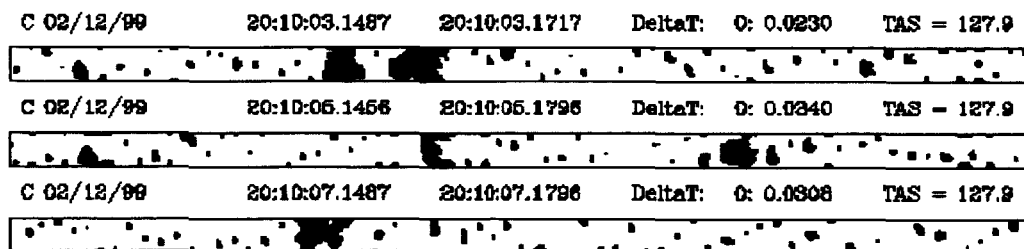


Fig. 24: 2D-C images of ice crystals from 2/12/99.

c) Sample Day: August 18th, 1999, KWAJEX

A quick case study is presented here to illustrate how an example updraft core appears, and how the sampled convection can change over a short time period. We will

return to this data in Section 5 when environmental characteristics and parcel theory are discussed.

The Citation flew a research flight on August 18th, 1999 to sample cloud microphysical data. During the flight, areas of convective and stratiform precipitation were encountered. All of the updraft cores that qualified for this study were sampled in a line of convective cells to the southwest of Kwajalein, in the southwest part of the western dual-doppler lobe (Fig. 25). The radar showed that the precipitation was moving westward and fluctuating in intensity. Passes through this line of cells were made at 4.3, 4.6, 4.9, and 5.2 km. Individual cells were not sampled twice during the same altitude leg. Altitude and cloud particle concentrations are shown in Fig. 26. According to the flight notes, the cells had weakened by the time that the Citation made the pass at 5.2 km, so the line was abandoned and the Citation moved on to another area.

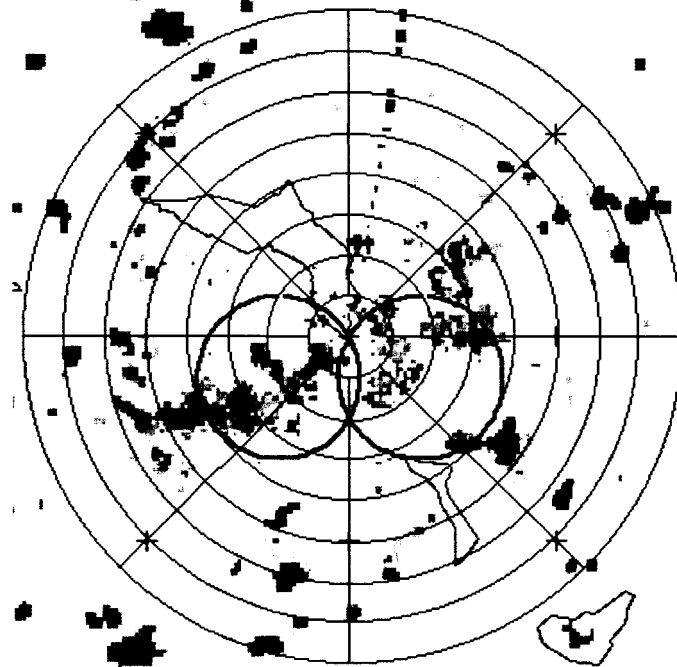


Fig. 25: Radar scan at 2:20 UTC on August 18th, 1999. The Citation sampled the cells to the southwest of the radar in the western dual-doppler lobe. Image courtesy of the University of Washington.

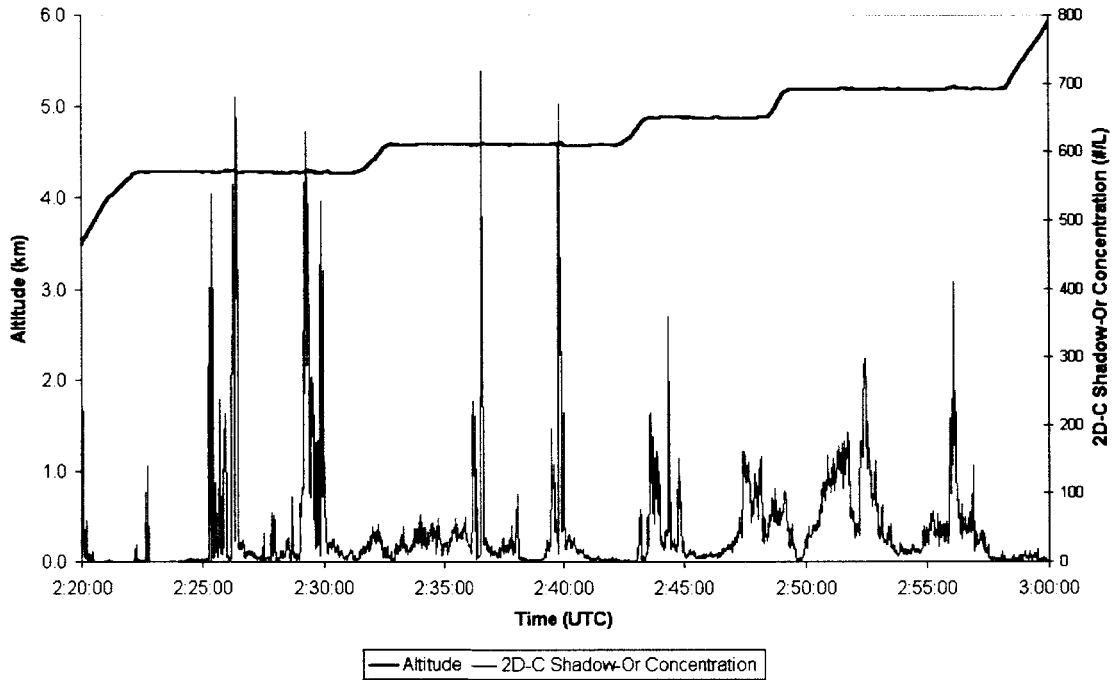


Fig. 26: Altitude and cloud particle concentrations from the 2D-C probe from 2:20 to 3:00 UTC on August 18th.

The list of updraft cores is given in Table 4. There were 13 events that fit the updraft core definition, with at least three per altitude leg. Maximum updraft speeds ranged from 1.3 m/s to 8.3 m/s. Widths ranged from over 2.5 km to barely in excess of the 0.5 km minimum needed to be considered a core. As can be seen by matching the updraft core times to the cloud particle concentrations, there is a direct correlation. What can also be seen is that the particle concentrations were lower in the last two passes, which correlates well with the decreased intensity of the cores and the observations of the weakened cells. Despite knowing the flight track and location of the updraft cores, it was not possible to conclusively determine if the Citation sampled the same updraft core more than one time.

Table 4: Characteristics of updraft cores sampled on 8/18/99.

Start Time (UTC)	End Time (UTC)	Width (m)	Maximum Speed (m/s)	Average Speed (m/s)	Altitude (m)	Temp. (°C)
2:25:44	2:25:56	1308	2.9	1.7	4277	1.9
2:26:09	2:26:25	1773	6.9	4.7	4288	1.9
2:29:11	2:29:35	2578	5.5	3.3	4284	1.7
2:36:35	2:36:39	521	5.9	4.5	4582	-0.1
2:39:27	2:39:31	550	2.6	2.0	4581	-0.2
2:39:46	2:39:54	1020	8.3	5.5	4590	-0.2
2:44:29	2:44:33	551	1.4	1.2	4881	-0.7
2:44:36	2:44:41	669	2.0	1.7	4883	-1.1
2:44:43	2:44:50	890	2.4	1.9	4883	-1.6
2:46:15	2:46:20	615	1.3	1.1	4876	-1.1
2:53:44	2:53:50	733	2.2	1.6	5188	-3.5
2:56:00	2:56:22	2461	5.0	2.4	5206	-3.7
2:56:24	2:56:39	1736	2.7	1.8	5195	-4.0

An example of one of the updraft cores is given in Fig. 27. The liquid water content from the King probe and the vertical wind are plotted for a one-minute period from 2:36:00 to 2:37:00 UTC. There is good correlation between the location of the updraft core (2:36:35 to 2:36:39) and the higher amounts of liquid water. However, the highest liquid water content value in this core is not at the time of the strongest vertical velocity. There is also another pocket of increased liquid water content that is not associated with an updraft core.

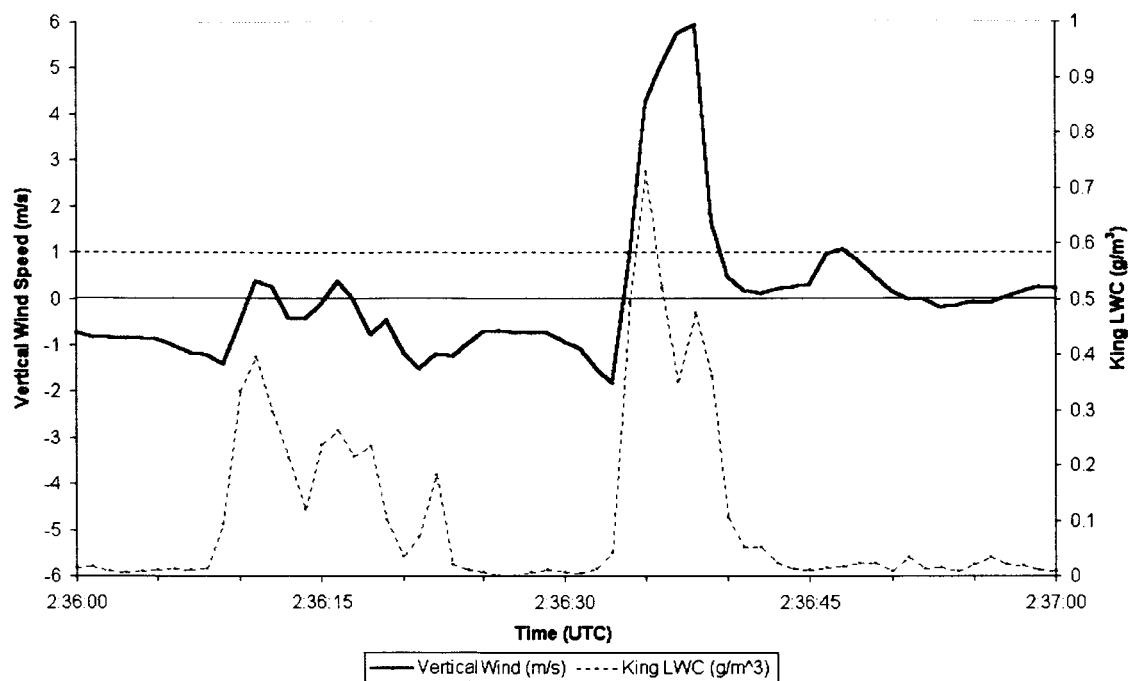


Fig. 27: Vertical wind speed and King liquid water content from an updraft on August 18th, 1999.

COMPARISONS WITH OTHER STUDIES

The results from LBA and KWAJEX are directly compared to other aircraft data, and qualitatively compared to the radar, profiler, and model data in this section. Some of the previous aircraft studies about tropical convection are shown in Table 5. The data from LBA, KWAJEX, GATE, TAMEX, and EMEX, along with Atlantic hurricane eyewalls and rainbands (Jorgensen et al. 1985, Black and Hallett 1986) and the Thunderstorm Project (Byers and Braham 1949) are used in the comparisons. The Thunderstorm Project data was adapted from Zipser and LeMone (1980).

Figure 28 shows the median value of the average updraft core speeds for each project. Obviously, the midlatitude continental Thunderstorm Project values (cumulonimbus clouds

Table 5: Previous aircraft studies of tropical oceanic updraft cores.

<u>Project</u>	<u>Paper Cited</u>	<u>Year of Project</u>	<u>Location of Project</u>	<u>Number of Cores</u>
GATE	LeMone and Zipser 1980 Zipser and LeMone 1980	1974	Atlantic Ocean, off West Coast of Africa	253
MONEX*	Warner and McNamera 1984	1978-79	South China Sea, Arabian Sea, Bay of Bengal	99
TAMEX	Jorgensen and LeMone 1989	1987	Waters surrounding Taiwan	92
EMEX	Lucas et al. 1994	1987	North of Australia	511
TOGA COARE	Igau et al. 1999	1992-93	Western Pacific	268

*MONEX cores were not calculated in the exact manner as cores in the other studies, so direct statistical comparisons were not made.

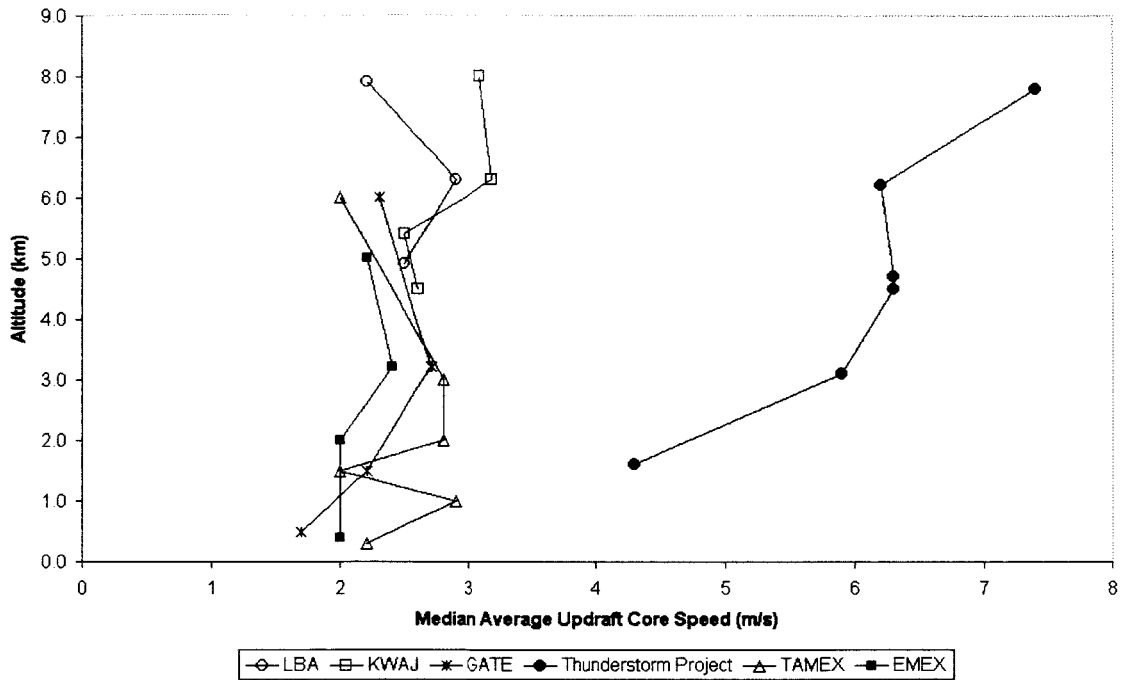


Fig. 28: Median values of average updraft core speed, from aircraft observations.

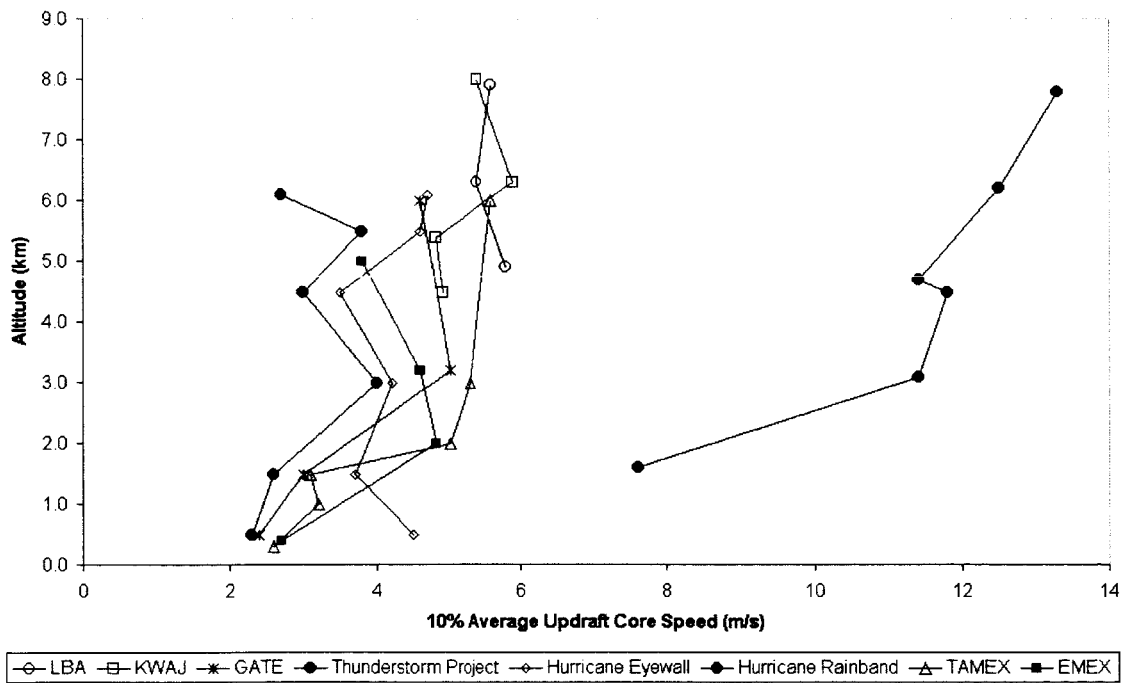


Fig. 29: 10% values of average updraft core speed, from aircraft observations.

sampled in Ohio and Florida) are much higher than the rest of the projects. Setting that aside, it is apparent that the studies from tropical areas are consistent. All of the tropical values fell within the standard deviation of the average updraft core speed from LBA and KWAJEX.

The 10% values of the average updraft core speed (Fig. 29) show that the Thunderstorm Project is again much stronger than the other studies. The tropical studies are similar, with the hurricane rainband having the weakest updraft cores while TAMEX, LBA, and KWAJEX have the strongest cores (above 2.0 km).

The median values of the maximum updraft core speeds are shown in Fig. 30. The largest difference between the studies is around 6.0 km where the LBA and KWAJEX values are higher than GATE and TAMEX. However, all of the values fall within the standard deviation of the maximum updraft core speeds for LBA and KWAJEX at that level (2.9 m/s).

The 10% maximum updraft core speeds, given in Fig. 31, show that most of the values increase with height. At 1.0 km, the values range from around 4.0 to 6.0 m/s, while at 6.0 km the values range from 8.0 to 10.0 m/s. The two main outliers are the hurricane eyewall at 0.5 km and LBA at 5.0 km. The standard deviation for LBA at 5.0 km is 3.5 m/s. The weakest updraft cores were again found with the hurricane rainband, while the strongest updraft cores were from LBA and KWAJEX at the higher altitudes.

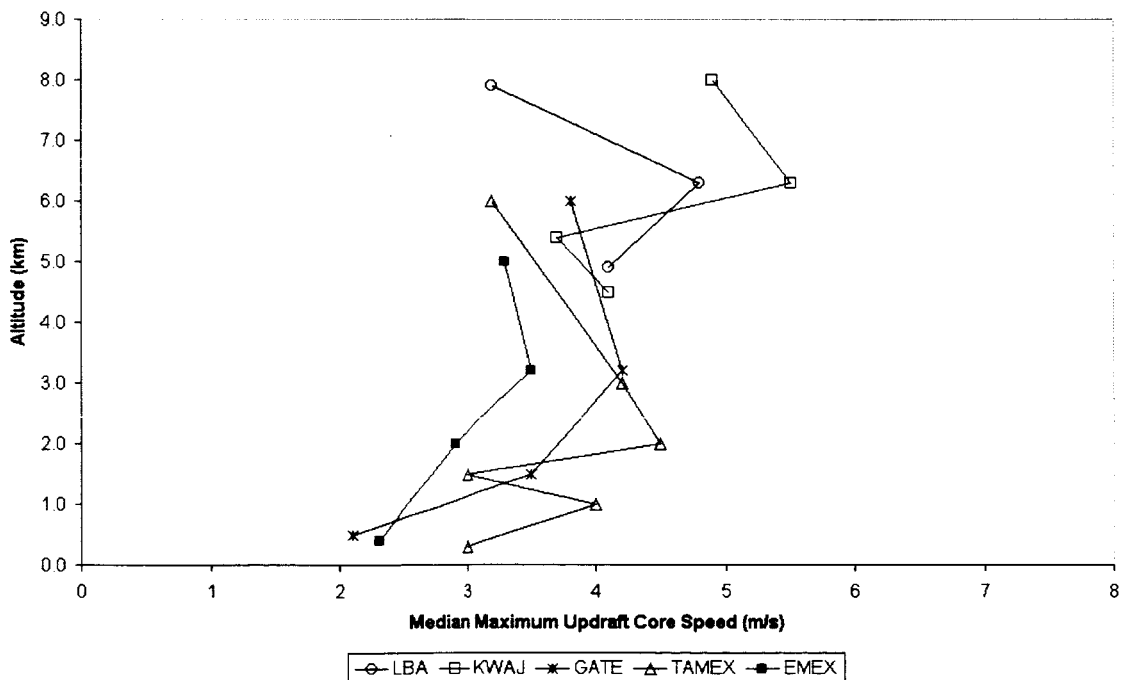


Fig. 30: Median values of maximum updraft core speed, from aircraft observations.

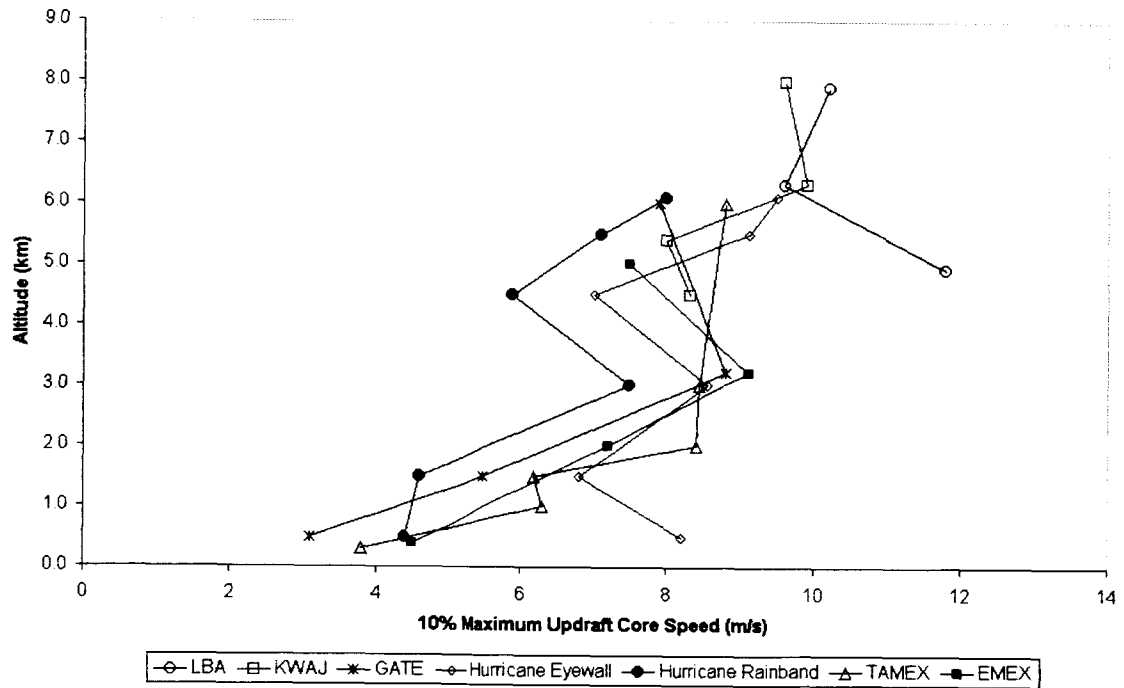


Fig. 31: 10% values of maximum updraft core speed, from aircraft observations.

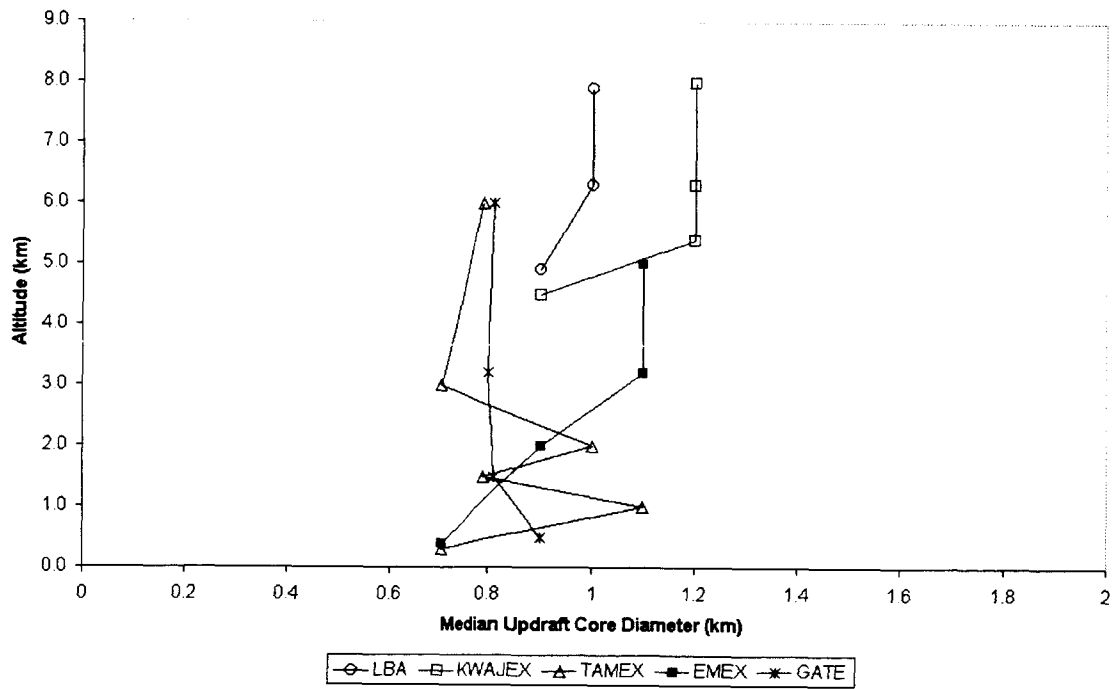


Fig. 32: Median diameters of updraft cores, from aircraft observations.

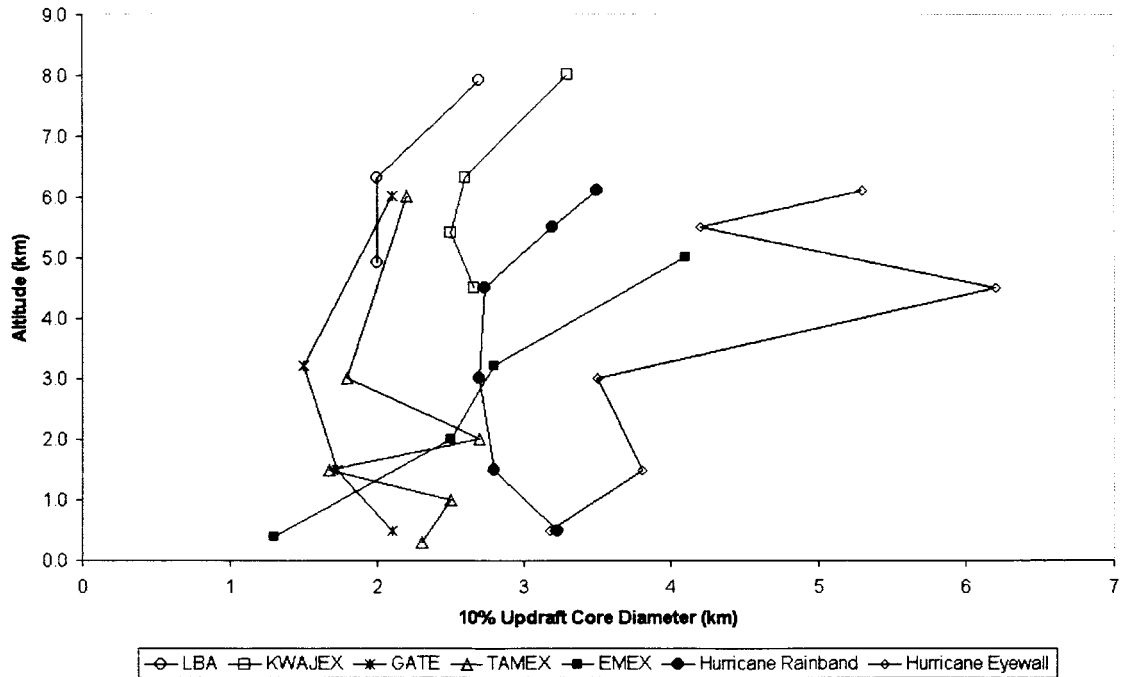


Fig. 33: 10% values of updraft core diameter, from aircraft observations.

Figure 32 shows the median diameter of the updraft cores. Most of the studies show a steady size or a slightly larger core with increased altitude. The 10% values in Fig. 33 show an increasing diameter with altitude for almost all of the projects. The hurricane eyewall updraft cores are the largest and those values are outside of the standard deviation of LBA and KWAJ.

The amount of mass flux is dependent on both updraft core speed and width (as well as density). Knowing these quantities, it would make sense that the differences that were found in the speed and size of the updraft cores earlier would show up in the comparisons of the mass flux values. The median mass flux values are shown in Fig. 34. The values decrease with increased altitude. This is likely due to the the air density decreasing while the updraft core strength and width are fairly constant. The high values for TAMEX at low levels are interesting, but they may be an artifact of the small number of cores sampled (92 cores divided up into 6 altitude ranges).

The 10% values of mass flux are shown in Fig. 35. Not surprisingly, due to their width, the highest values are from hurricane eyewalls. GATE, TAMEX, and LBA all are on the weaker side, with mass flux values below $6 \times 10^3 \text{ kg m}^{-1} \text{ s}^{-1}$. Meanwhile, 10% values for KWAJEX and EMEX peak in excess of $1 \times 10^4 \text{ kg m}^{-1} \text{ s}^{-1}$. Though the data was not readily available, it seems that all of the tropical mass fluxes would pale in comparison to the mass flux during the

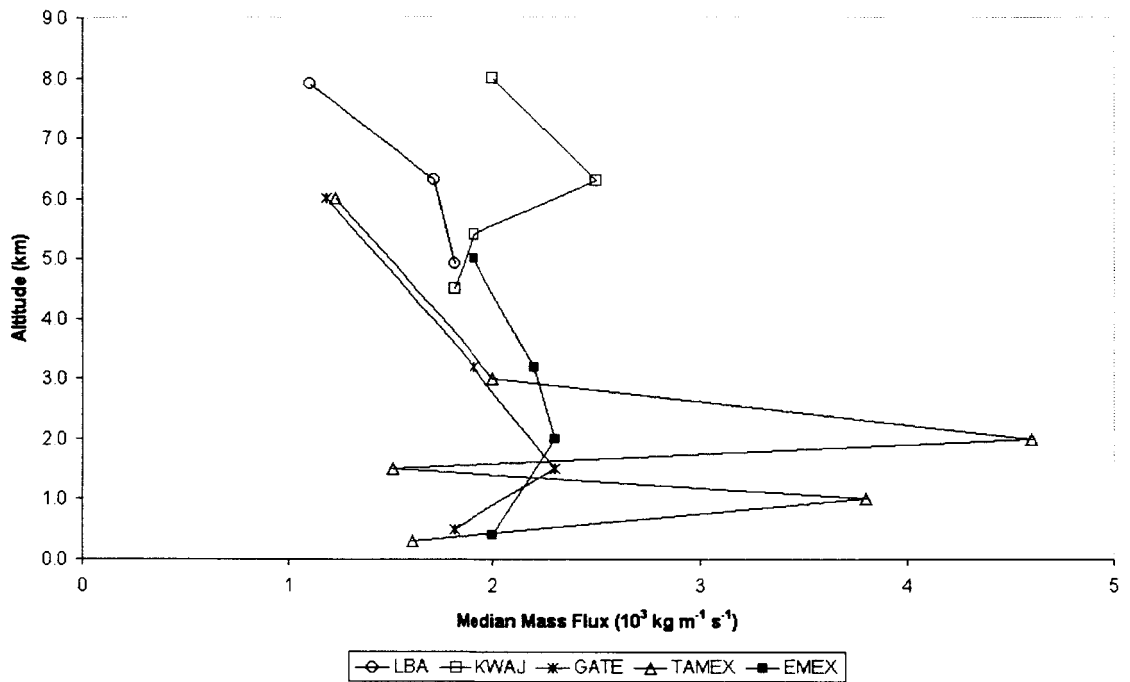


Fig. 34: Median values of mass flux, from aircraft observations

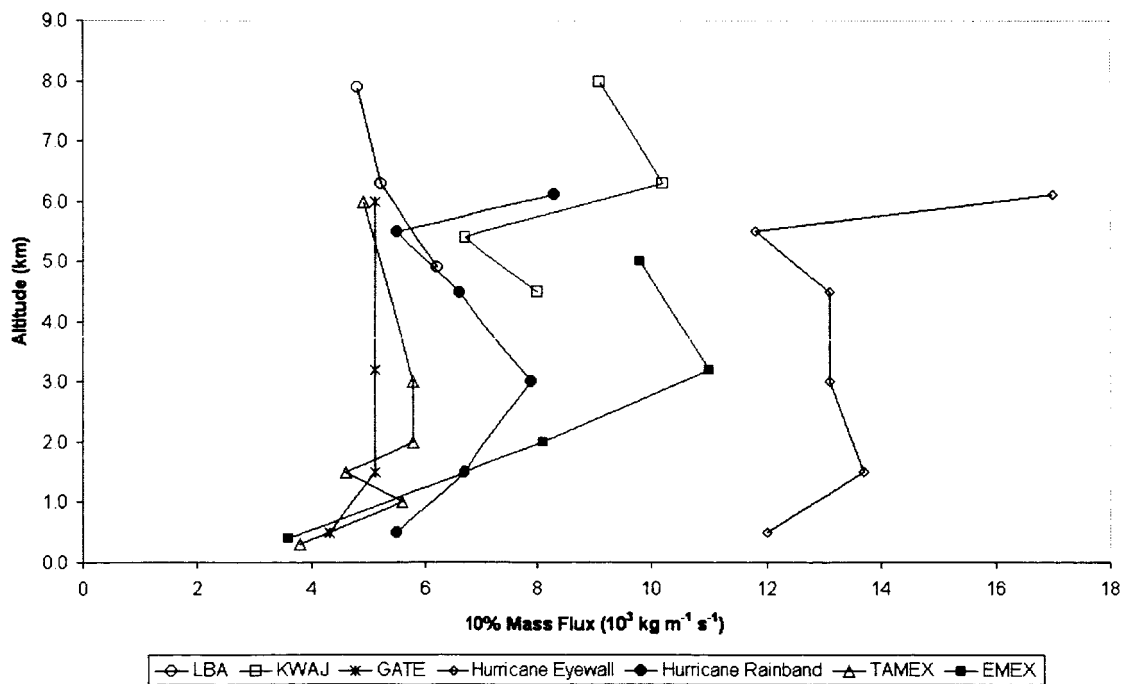


Fig. 35: 10% values for mass flux from aircraft observations

Thunderstorm Project. Looking again at Figs. 28 and 29, and then noting that the Thunderstorm Project had diameters that were larger than the ones from tropical studies

(May and Rajopadhyaya 1999, their Fig. 14), we could see that the mass fluxes would easily exceed the values from the tropical projects.

In addition to the projects involved in the comparisons above, there have been several other studies that have collected data from tropical convection. As was stated earlier, cores from MONEX were not calculated in the same manner as the other studies. However, the authors were able to state that their results were “generally consistent” with those determined from GATE (Warner and McNamera 1984). Similar results were found during TOGA COARE, held in the western Pacific. A study of Hurricane Emily showed stronger updraft cores, and widths that were about three times as wide as GATE (Black et al. 1994). The maximum updraft encountered was 23.9 m/s, which is high when it was shown that no updraft sampled during GATE, LBA or KWAJEX surpassed 17 m/s. This shows that hurricane eyewalls can have larger and stronger updrafts than other tropical convection.

Profiler and radar observations can also be used to compare with the aircraft data. These remote sensing techniques have a temporal and spatial advantage over the aircraft data. However, we are not able to directly compare the values of updraft core strength and width because the remote sensing instruments do not replicate the same data

Table 6: Profiler and radar measurements of the altitude of maximum vertical velocity in tropical convection

Paper Cited	Location	Type	Height of max VV	Type of system
Balsley et al. 1988	Pohnpei Is, Pacific Ocean	Profiler	11+ km	Various convection
Cifelli and Rutledge 1994	Darwin, Australia	Profiler	3 and 9 km	MCS
Chong et al. 1983*	West Africa	Radar	7 km	MCS
May and Rajopadhyaya 1999	Darwin, Australia	Profiler	4 and 10+ km	Various convection
Cifelli et al. 2002	Brazil	Radar	8 to 10 km	MCS

*Data from Cifelli and Rutledge 1994

needed for the updraft core definition. The characteristic of vertical motion that we can look at is the height of the maximum updraft speed. Table 6 shows several studies from profilers and radars. The height of the maximum vertical velocity is variable, depending on location, type of convection and time of year, but all of the studies show a peak at an altitude higher than most of the aircraft data.

Another way to compare the characteristics of updraft cores is not by direct observation, but by computer modeling. Xu and Randall (2001) took the atmospheric conditions from GATE and ran a model to simulate the convection. In their study they were able to determine data from over 6600 simulated updraft cores, in relation to the 253 that the aircrafts sampled. They were also able to obtain results from heights up to 15 km. The simulations and observations agreed fairly well. There was a difference in average updraft core speed of only 0.5 m/s at most heights. However, they found that the peak level of the updraft core speed occurred near 6 km, which is significantly higher than the 3 km that the data from the aircraft suggested. The authors note that this discrepancy could be due to the poor vertical resolution of the observations and

simulations. Donner et al. (2001) described a cumulus parameterization in a general circulation model. Their vertical velocity findings indicate a maximum updraft level between 11 and 12 km.

There are a few things that become apparent when looking at the data from research aircraft and remote sensing instruments. First, tropical updraft cores are much weaker than their mid-latitude continental counterparts. This has been described in previous literature, and the results from this study add to the documentation.

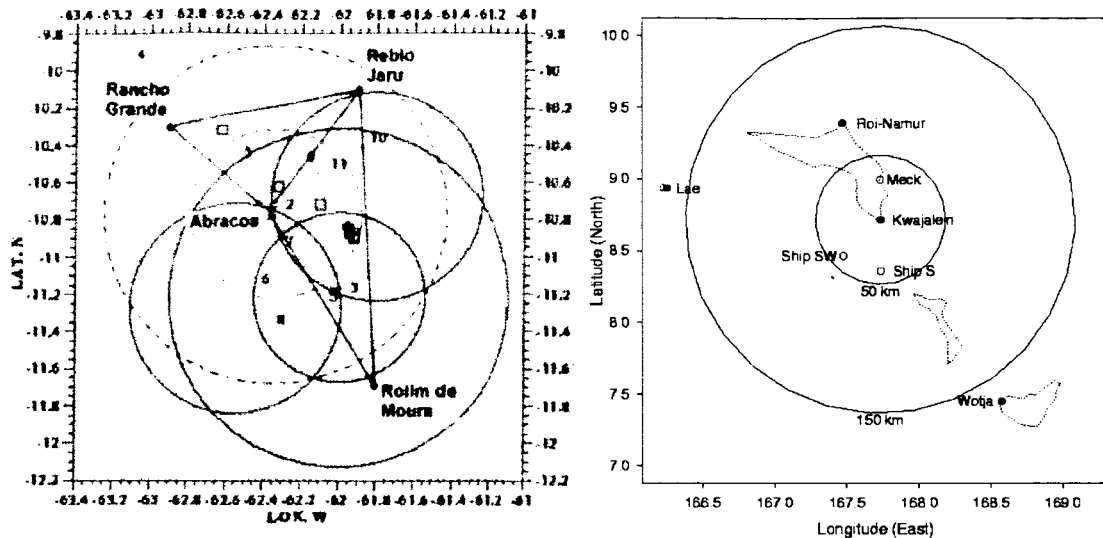
Secondly, the remote sensing and computer model data indicate that updrafts continue to increase in strength above the altitude of most of the aircraft observations. However, the only statistics from aircraft observations that solidly indicate an increase in updraft core strength with height is the 10% maximum updraft core speed. A reason for the difference may be due to a sampling bias. The aircraft are not able to sample the most intense part of the convective storms. For example, during LBA, Atlas and Williams (2003) used a profiler to sample a 24 m/s updraft and Cifelli et al. (2002) sampled a 20+ m/s updraft by dual-doppler data analysis. Both of these updrafts were significantly stronger than any core sampled by the Citation during LBA. This bias would not affect the comparisons of the aircraft data, but could explain the difference between the aircraft and remote sensing data.

PARCEL THEORY

It has been determined, through this study and others, that tropical updraft cores are weaker than their midlatitude continental counterparts. However, the reason for these weaker tropical updraft cores is not known as well. Many authors have discussed this topic in their papers. Early on, some authors attributed the difference to the amount of CAPE available over the oceans versus land. Since the CAPE theories were mainly disregarded, many authors have looked at buoyancy, water loading, boundary layer depth, CIN, etc. as possible factors (Szoke and Zipser 1986, Jorgensen and LeMone 1989, Lucas et al. 1994, Michaud 1996, Lucas et al. 1996, Wei et al 1998).

a) Environmental characteristics

TRMM-LBA and KWAJEX both had an extensive observational network that included several sounding sites (Figs. 36 and 37). When plotting the locations of the updrafts sampled during the projects (not shown), there is a fairly even distribution throughout the observational area. Therefore, not one sounding site was favored over the others. The sounding data sets were not perfect, due to various



Figs. 36 and 37: Locations of the sounding sites for TRMM-LBA and KWAJEX. Figures are from the TRMM and University of Washington sounding websites, respectively.

problems. Documented problems and quality control measures taken with the TRMM sounding dataset can be found at http://trmm.gsfc.nasa.gov/trmm_soundings/soundings.html. Trying to find the best sounding to capture the atmosphere in the vicinity of the clouds sampled on a particular day took some work. First, the biases of each sounding were checked. This eliminated a couple of the sites in which the humidity measurements were suspect. Also important was the state of the atmosphere around the site. The sounding may have sampled an area affected by nearby storms or an outflow region. The radar data for each sounding time was checked to eliminate contamination and to try to find the best area for a sounding (ahead of the convection, preferably). The last step was to check for cloud bases and to match them with LCL and CCL data from the sounding. Unfortunately, for LBA there was not much data available about the cloud bases, so only four flight days were identified as having soundings with acceptable accuracy. KWAJEX soundings had much less variability, and there was also complete cloud base data from the ceilometer on the Ron Brown research vessel. Therefore, 15 flight days worth of sounding data were chosen for KWAJEX. However, one of the major comparisons involves liquid water data from the airplane, and during KWAJEX the availability of the liquid water content data was a problem (Section 2). Only 6 flights during KWAJEX have sounding data and liquid water content data.

Table 7 shows some of the environmental characteristics of the atmosphere in and around the times that the Citation intercepted convection. One of the first things that jumps out is the variability in CAPE. CAPE measurements are highly susceptible to small changes, especially in the lowest 100 mb of the atmosphere (Bluestein 1993). Therefore, the absolute uncertainty involved with these CAPE values is likely on the order of ± 700 J/kg. One of the early theories about the lower updraft speeds over oceanic areas was that it was due to lower CAPE values. It was then determined that the CAPE values in oceanic areas were not that much different than over the midlatitude continental areas, but the amount of buoyancy was lower (Szoke and Zipser 1986, Lucas

et al. 1994). This can be explained by the height of the equilibrium level, which is higher in tropical areas. When integrating CAPE in the tropics there is more of the atmosphere available to reach a certain CAPE

Table 7: Environmental characteristics of the atmosphere in the vicinity of the time and area of sampled convection. A mean lower layer of 50 mb was used when lifting the parcel.

Date	Level of Max Buoy. (mb)	Max Buoy. (°C)	CAPE (J/kg)	CIN (J/kg)	LCL (mb)	Sat. Mixing Ratio at LCL (g/kg)	LFC (mb)	Equil. Level (mb)	Depth of Pos. Bouy. (mb)	NCAPE (J/(kg mb))
LBA										
2-1	300	3.0	1136	17	898	16.5	853	151	702	1.6
2-12	350	8.0	3077	3	902	18.4	894	123	771	4.0
2-13	350	3.0	1199	15	877	12.8	836	159	677	1.8
2-18	550	2.0	217	68	893	13.5	751	288	463	0.5
KWAJEX										
8-10	400	2.0	430	52	947	15.3	752	196	556	0.8
8-14	500	4.0	1564	1	945	17.1	923	144	779	2.0
8-18	350	7.0	2571	1	965	18.1	949	141	808	3.2
8-19	470	4.0	1507	2	948	16.7	936	140	796	1.9
8-22	500	5.0	1722	3	943	17.1	915	148	767	2.2
8-25	300	7.0	2793	0	955	19.8	952	137	815	3.4
8-26	250	8.0	2880	0	967	20.3	961	151	810	3.6
8-28 (5Z)	600	4.0	1692	0	949	18.5	939	146	793	2.1
8-28 (23Z)	600	4.0	1132	8	970	18.1	912	172	740	1.5
9-1	500	5.0	1798	6	948	16.9	913	149	764	2.4
9-2	400	5.0	1887	4	960	18.5	931	149	782	2.4
9-5	300	6.0	2072	4	955	17.5	933	145	788	2.6
9-8	500	6.0	1917	2	960	17.2	944	164	780	2.5
9-10	250	6.0	2503	0	970	19.4	970	138	832	3.0
9-11	400	3.0	556	38	955	15.3	912	202	710	0.8

value. These soundings were referred to as “skinny”, due to the buoyancy amounts being lower (Lucas et al. 1994). Since both LBA and KWAJEX were located within 15° of the equator, the equilibrium levels were nearly the same. However, cloud bases, LCLs, and LFCs were much lower over the oceanic KWAJEX sites than the continental LBA sites. This means that the area between the LFC and equilibrium level over the oceans was greater than over the land. In continental midlatitude regions, the area between the LFC and equilibrium level would be much less, due to the deeper boundary layer and lower tropopause. Taking this into consideration, we can look at something called “normalized CAPE” (NCAPE), which is the amount of CAPE divided by the depth of positive buoyancy (Blanchard 1998). For LBA and KWAJEX, the amount of NCAPE is well correlated with the amount of maximum positive buoyancy (R^2 value of 0.92).

The saturation mixing ratio at cloud base is generally higher for the lower LCL’s during KWAJEX. A higher saturation mixing ratio at cloud base would lead to a higher likelihood of precipitation for clouds of the same depth (Cotton and Anthes 1989). This

adds to the idea that precipitation fallout may be a significant reason why there was less liquid water content for the cores in KWAJEX.

The CAPE values from LBA and KWAJEX are very consistent with the values from EMEX as reported by Lucas (1993). The mean of the CAPE values for that project was 1765 J/kg, while the mean of the values from Table 7 is 1719 J/kg. The range was broader for LBA and KWAJEX than EMEX.

Halverson et al. (2002) reported on the environmental characteristics of the zonal wind regimes during LBA. The regimes were defined by the direction of the low-level wind (easterly, westerly, or neutral). It was determined that CAPEs were higher during the easterly regimes and that the precipitation during this time was more convective. Unfortunately, the regime was never westerly during the time that the Citation sampled, so no comparisons can be made between updraft core properties in the easterly and westerly regimes. An interesting point that the Halverson et al. paper brought up was that deep convective growth occurred around 1500 UTC (1100 LST) during LBA. This is important because almost all of the updraft cores sampled by the Citation occurred between 1800 and 2200 UTC. So the Citation may have missed most of the growth stages of the convective clouds.

b) Parcel Theory

According to parcel theory, CAPE is known as a predictor of the maximum amount of vertical velocity that a parcel can realize. The maximum updraft speed is given by the equation: $W_{\max} = \sqrt{2 * CAPE}$. Obviously, many other factors contribute to the actual vertical velocity of a parcel, such as water loading, entrainment and dynamic forcing. With the data that was sampled during the two projects, we can try to get an indication of how much of the maximum vertical velocity was realized by each of the updraft cores. To accomplish this, the amount of CAPE integrated up to the level of the intercepted core was calculated. These CAPE values were then inserted into the equation above to find the theoretical maximum vertical velocity for each sampled updraft core. The theoretical values were then compared to the actual maximum updraft core speeds sampled by the Citation. The distribution is found in Fig. 38. What can be seen by this figure is that the

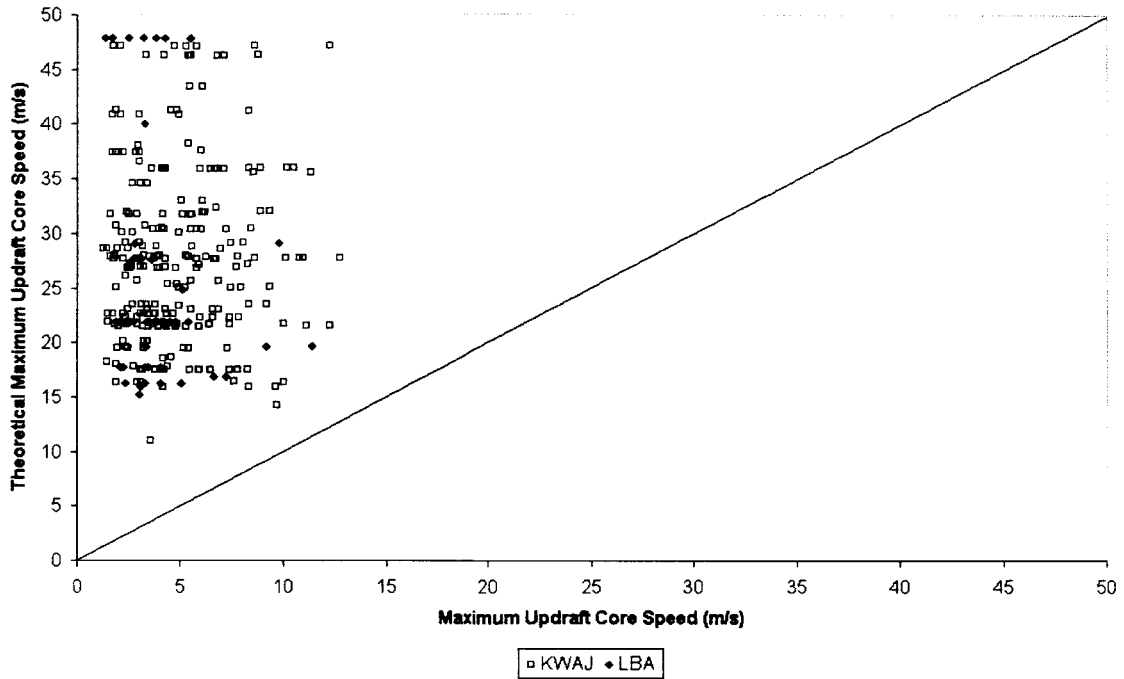


Fig. 38: Theoretical vs maximum updraft core speeds, and a 1:1 line.

maximum updraft core speeds that were sampled are far below the theoretical values. The largest theoretical values are near 50 m/s while the actual maximum peak updraft sampled in this subset of cores was 12.7 m/s. Figure 39 shows the same thing, but with the fraction of the theoretical maximum vertical velocity realized versus altitude. What is seen is the effect of the CAPE, and therefore theoretical maximum vertical velocity, increasing with height while the actual maximum updraft core speeds do not increase as rapidly (as shown in the Section 3). Therefore, the percentage of the theoretical maximum vertical velocity decreases with height. Looking at Fig. 40, we find only a weak correlation between the width of the updraft core and the fraction of theoretical maximum vertical velocity.

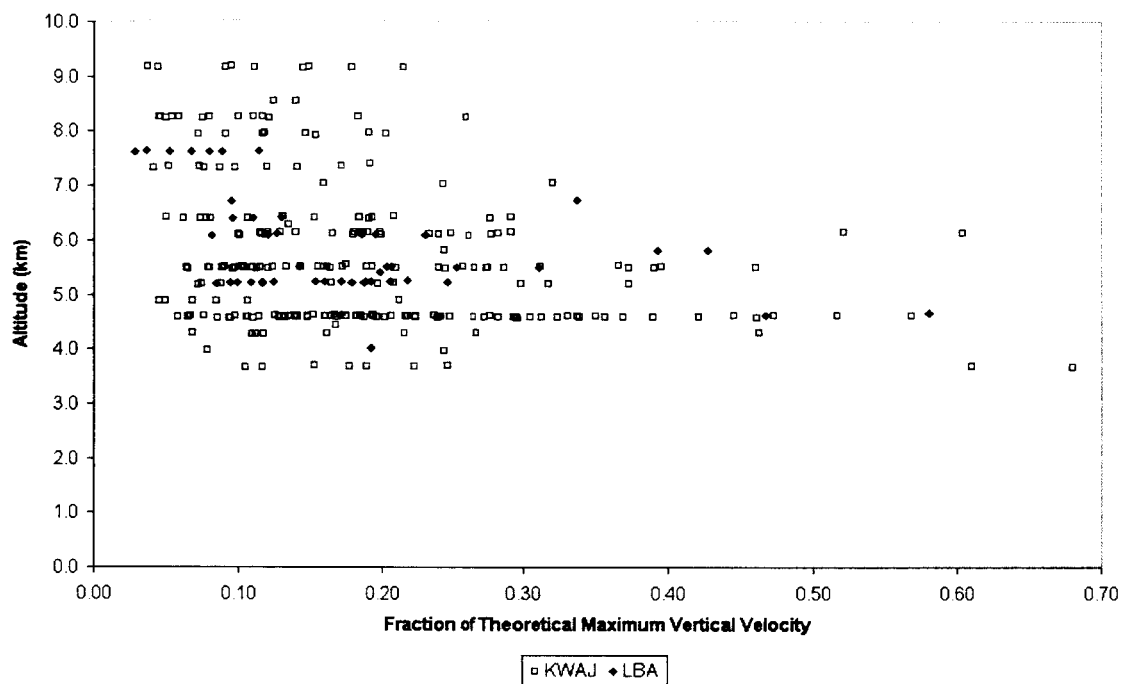


Fig. 39: Fraction of theoretical maximum vertical velocity vs altitude.

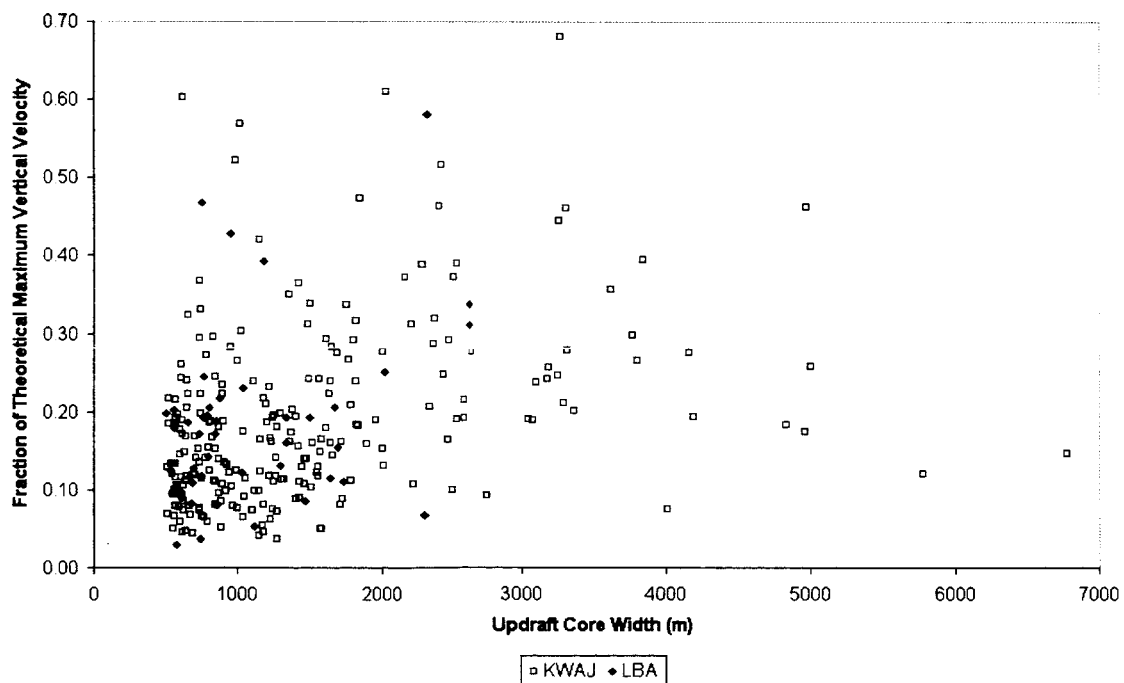


Fig. 40: Width of updraft core vs fraction of theoretical maximum vertical velocity realized.

The results from GATE, EMEX, TAMEX, and Atlantic hurricanes also show that very low percentages of the theoretical vertical velocity are realized (Lucas 1993). The

reported percentages in those cases (around 10%) were much lower than the ones from this study because they used the CAPE from the entire depth of the atmosphere, whereas the CAPEs used here were only integrated to the altitude where the Citation intercepted the updraft core. Igau et al. (1999) reported that CAPE values integrated to 500 mb during TOGA COARE were 360 ± 66 J/kg and GATE values were around 377 J/kg. In this study, the cores sampled near 500 mb had CAPEs ranging from 132 to 505 J/kg, with a majority from 362 to 424 J/kg. So the values from LBA and KWAJEX were slightly higher, but fairly close.

Percentages of theoretical maximum vertical velocity for updrafts from the Thunderstorm Project, a dryline tornadic storm, and a hailstorm updraft core were analyzed the same way as the other tropical studies, without reference to the altitude of the sampled updraft. However, the values (20 to 60%+) indicate that the fraction of theoretical maximum vertical velocity realized is higher for mid-latitude continental updrafts than for tropical updrafts (adapted from Zipser and LeMone 1980, Jorgenson and LeMone 1989, and Lucas et al. 1994b).

It is obvious from looking at Figs. 38 through 40 that the updraft cores measured in LBA and KWAJEX were not as strong as parcel theory predicted they should be. Entrainment and mixing is one of the ways that the updraft core speed could have been lowered, by reducing the buoyancy of the updraft. The liquid water content of a parcel is also strongly affected by entrainment and mixing. The adiabatic liquid water content of a parcel is defined as the total mixing ratio of an unmixed parcel minus the saturation mixing ratio of the parcel at a certain level. The parcel is assumed to originate at cloud base. The ratio of the actual liquid water content to the adiabatic value represents the effects of mixing (Cotton and Anthes 1989). From previous studies, it is known that the adiabatic value is rarely realized and that the ratio of liquid water content to its adiabatic value decreases with height (Pruppacher and Klett 1997, Pontikis and Hicks 1993).

Precipitation-sized droplets had likely formed in many of the updrafts in LBA and KWAJEX by the time the cores were sampled. The removal of these droplets by gravity also could have lowered the liquid water content to below its adiabatic value. It would also decrease the water loading effect, by removing these heavier droplets.

Figure 41 shows the fraction of adiabatic liquid water content versus altitude. Since the King probe is a liquid water probe, the updraft cores that included ice particles were omitted. The phase of water was determined by temperature, 2D-C images and response from the Rosemount icing detector. As Fig. 41 shows, the fraction of adiabatic liquid water content is rather low, with most of the cases

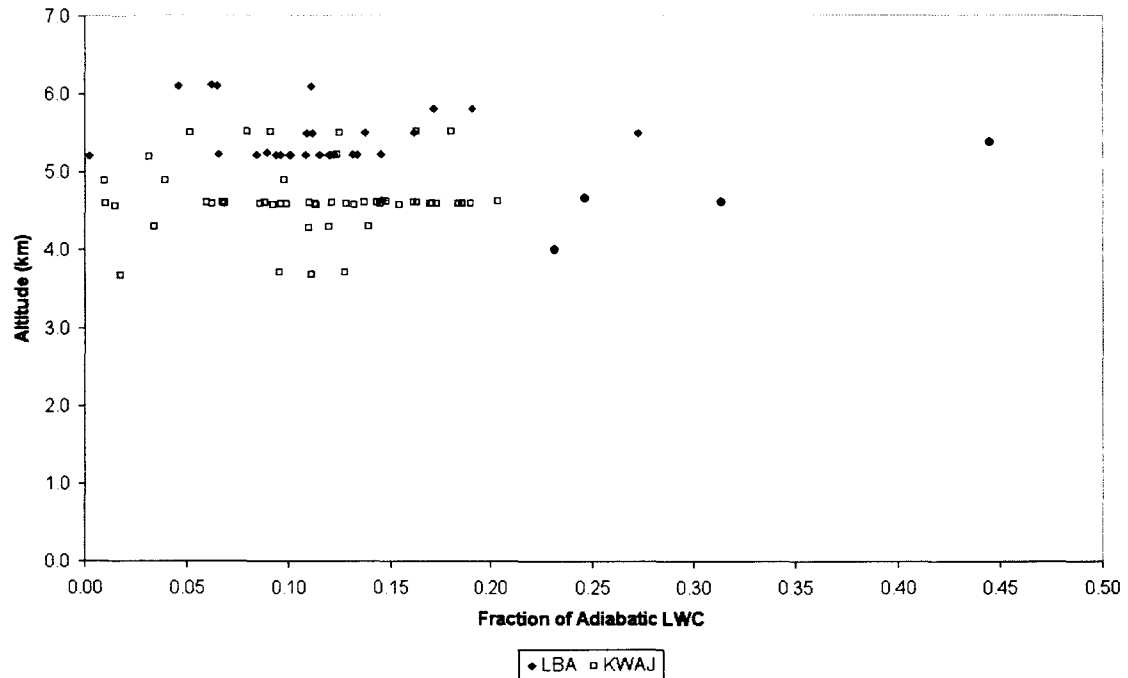


Fig. 41: Fraction of adiabatic liquid water content vs altitude.

below a quarter of the adiabatic value. This is in line with some previous studies that reveal ratios approaching asymptotic values on the order of 0.2 above 2 – 3 km (Cotton and Anthes, 1989). Lucas et al. (1994) noted that their liquid water contents were only a small fraction of the adiabatic values during EMEX and Wei et al. (1998) stated that during TOGA COARE “cloud liquid water contents were usually less than 0.1 of the adiabatic value, even in updrafts”.

Now that the theoretical maximum vertical velocities and adiabatic liquid water contents have been analyzed, we can compare them to each other to determine if there is a positive correlation (Fig. 42). Indeed, the closer that the liquid water content is to its adiabatic value, the closer

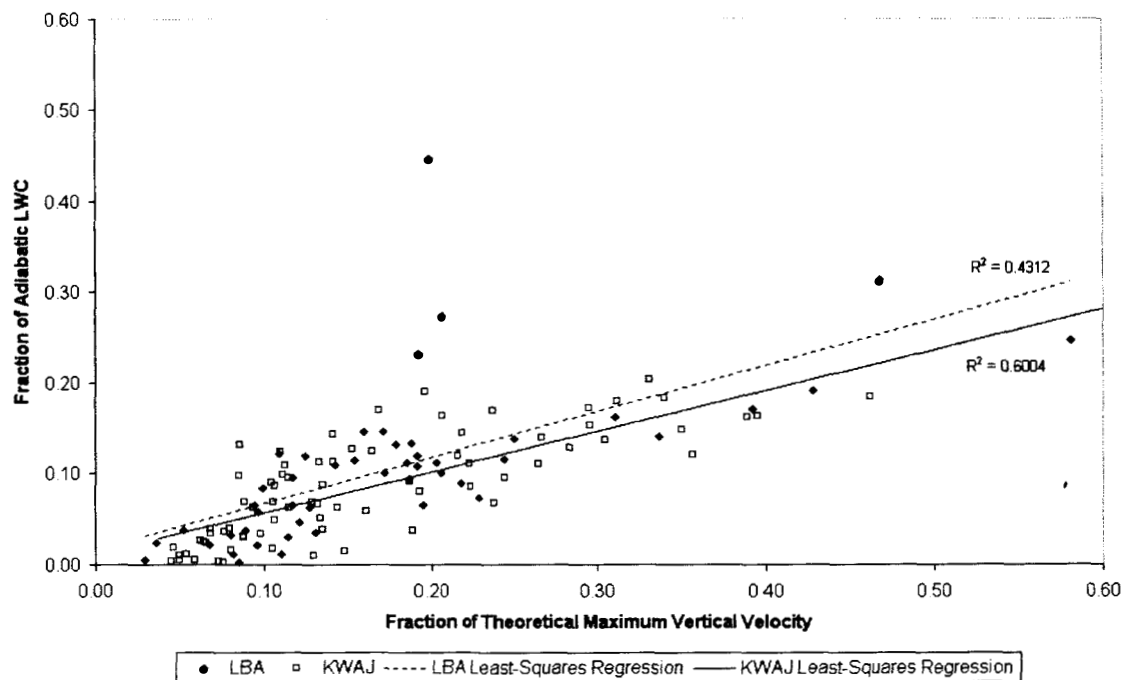


Fig. 42: Fraction of theoretical maximum vertical velocity vs fraction of adiabatic liquid water content.

that the maximum vertical velocity is to its theoretical value. This indicates that entrainment and mixing did likely play a role in reducing the buoyancy of the cores.

c) Sample Day

Returning to the August 18th, 1999 case study, we find that the atmosphere was very unstable that day, with CAPE values of 2100, 3400, and 2600 J/kg at three of the sounding sites. The Wotja site was chosen because it was undisturbed and the LCL matched up with the cloud base heights from the ceilometer on the Ron Brown. As shown by the sounding (Fig. 43), there was a good amount of buoyancy throughout the atmosphere, but especially from 400 to 250 mb where the

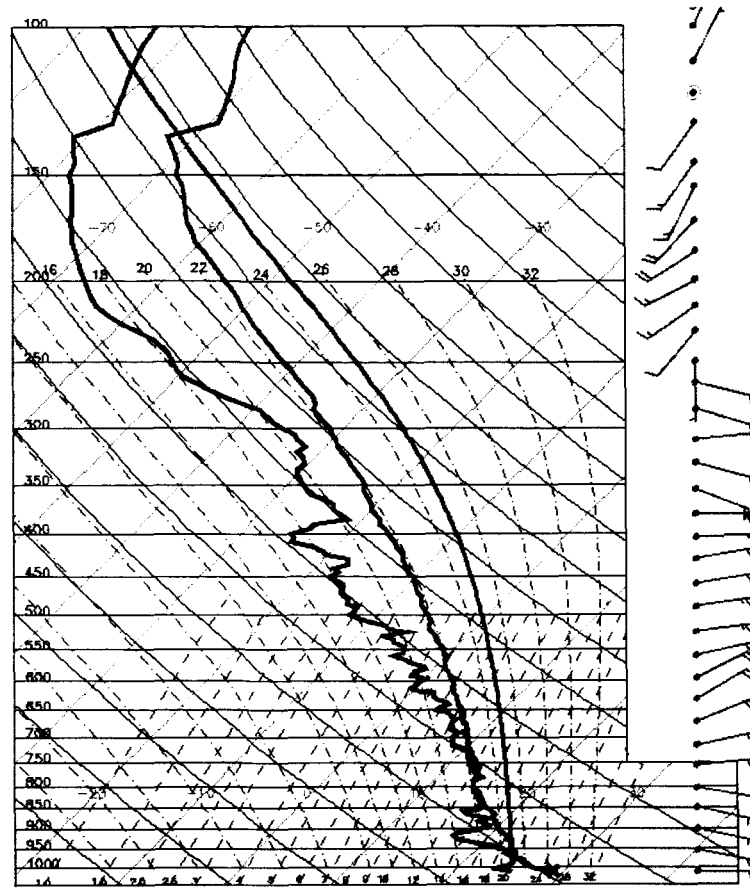


Fig. 43: Sounding from August 18th, 1999, courtesy of NASA.

Table 8: Characteristics of updraft cores sampled on 8/18/99

Start Time (UTC)	End Time (UTC)	Max Updraft (m/s)	Altitude (m)	CAPE (J/kg)	Theoretical Max VV (m/s)	% of Theo. VV	King LWC (g/kg)	Adiabatic LWC (g/kg)	% of Adiabatic LWC
22544	22556	2.9	4277	330	25.7	0.11	0.73	6.63	0.11
22609	22625	6.9	4288	330	25.7	0.27	0.92	6.63	0.14
22911	22935	5.5	4284	330	25.7	0.22	0.79	6.63	0.12
23635	23639	5.9	4582	368	27.1	0.22	0.99	6.86	0.14
23927	23931	2.6	4581	368	27.1	0.09	0.43	6.86	0.06
23946	23954	8.3	4590	368	27.1	0.30	0.94	6.86	0.14
24429	24433	1.4	4881	409	28.6	0.05	0.07	7.07	0.01
24436	24441	2.0	4883	409	28.6	0.07	0.28	7.07	0.04
24443	24450	2.4	4883	409	28.6	0.09	0.69	7.07	0.10
24615	24620	1.3	4876	409	28.6	0.05	0.03	7.07	0.00
25344	25350	2.2	5188	454	30.1	0.07	0.03	7.24	0.00
25600	25622	5.0	5206	454	30.1	0.16	0.90	7.24	0.12
25624	25639	2.7	5195	454	30.1	0.09	0.23	7.24	0.03

maximum buoyancy reached approximately 7°C. However, none of the updrafts sampled on the 18th were at a significant altitude (Table 8), so their CAPE values only ranged from 330 to 454 J/kg. Table 8 shows more characteristics of those 13 updraft cores sampled on August 18th, 1999. The theoretical maximum updraft speeds as predicted by parcel theory range from 25.7 to 30.1 m/s. Those values are significantly larger than what was actually encountered. None of the cores achieved more than 30% of the possible maximum vertical velocity, and over half did not reach 10% of the predicted value. The liquid water contents results were similar. Adiabatic liquid water contents ranged from 6.6 to 7.2 g/kg and no core recorded more than 14% of the

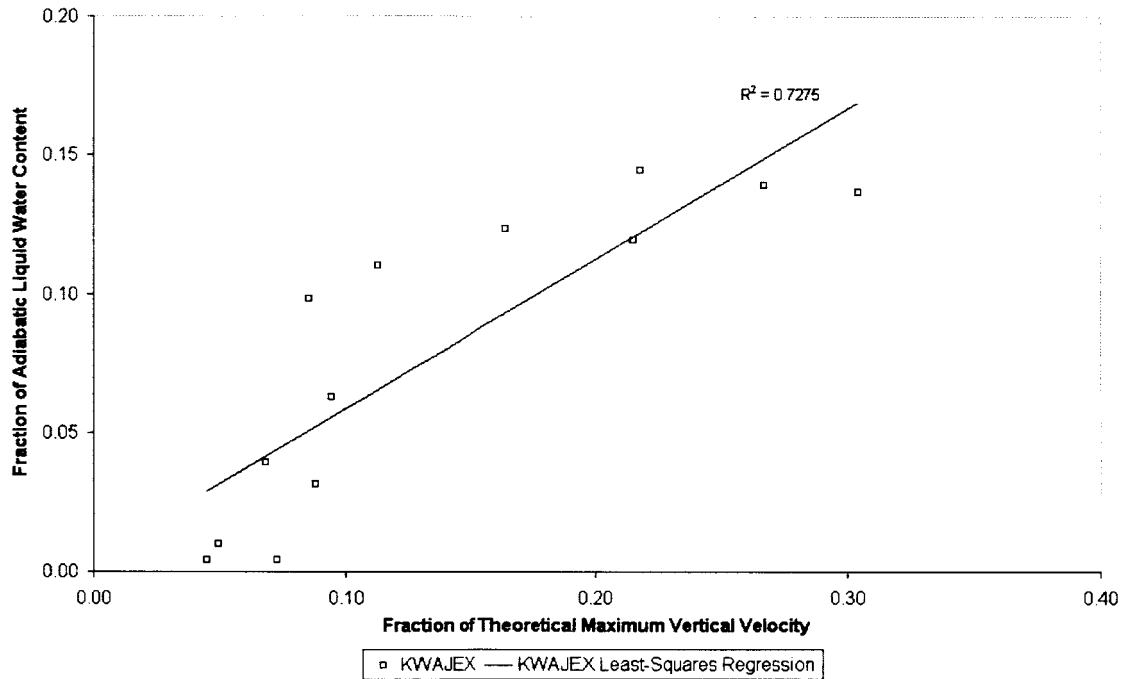


Fig. 44: Fraction of theoretical maximum vertical velocity vs fraction of adiabatic liquid water content for the updraft cores sampled on 8/18/99.

adiabatic value. When comparing the cores, like in Fig. 42, there is a solid correlation between the the fraction of adiabatic liquid water content and the fraction of theoretical maximum vertical velocity (Fig. 44).

DISCUSSION

The updraft cores sampled during TRMM-LBA and KWAJEX revealed interesting characteristics of tropical clouds. One of the most intriguing results was that there was no significant difference in strength between the updraft cores sampled over tropical continental areas and those sampled over tropical oceanic areas. While this may seem counterintuitive, there is precedent from other studies that have shown that the wet season convective characteristics from the Amazonian region are more like those of an isolated oceanic region than a continental region (Petersen and Rutledge, 2001). Also, May and Rajopadhyaya (1999) examined tropical continental convection with a profiler and found that there was an agreement between the oceanic and continental tropical updraft speed characteristics, which would match the results from this study.

The data from LBA, KWAJEX, and other tropical studies show that tropical updraft cores are weaker than midlatitude continental updraft cores. In Section 5, it was determined that entrainment and mixing likely played a role in reducing the vertical velocity of the updrafts. Entrainment and mixing have been mentioned as major contributors in many studies, such as Jorgensen and LeMone (1989), Lucas et al.

(1994a & 1994b), and Wei et al. (1998). Michaud (1996) and Lucas et al. (1996) discussed how the deeper boundary layer and higher CIN values help protect continental updrafts from the deleterious effect of entrainment of environmental air. Wei et al. used TOGA COARE data to state that the effects of entrainment and mixing are greater than the effects of precipitation water loading in reducing buoyancy.

Water loading is mentioned as another contributor to lower updraft core speeds in the studies above and in Szoke and Zipser (1986). Lucas et al. (1994) found that the amount of water loading was similar for tropical and continental areas, but that its effects were more pronounced for tropical areas because buoyancy was lower.

Entrainment and water loading are likely the major contributors to the low tropical updraft core speeds. However, both factors also affect midlatitude continental clouds, so that does not fully explain why tropical updrafts are weaker. The probable reason for the weaker tropical updrafts is that any reduction of buoyancy from entrainment or water loading would be a greater fraction of the total buoyancy. This is the "skinny" sounding idea from Lucas et al. 1994. Midlatitude continental soundings show a greater amount of buoyancy over a shorter depth so the reduction of buoyancy from entrainment and water loading of 2°C would not be as important as it would be to the lower buoyancy values from tropical areas.

SUMMARY

The University of North Dakota's Cessna Citation II research aircraft sampled tropical clouds during missions in the Amazon (TRMM-LBA) and the middle Pacific (KWAJEX). Vertical velocity data was analyzed to find updraft cores in convective clouds. The characteristics of these updraft cores were studied to determine the differences between tropical oceanic and tropical continental convection. LBA and KWAJEX were also compared to other studies of updraft cores. Reasons for the weak nature of tropical updraft were then investigated. Here is a summary of the findings:

1. Updraft cores from LBA and KWAJEX were similar in strength, which was determined by looking at the 10% and 50% values of average and maximum updraft speeds. Cores from KWAJEX were slightly larger, which contributed to a higher amount of mass flux.
2. Cloud liquid water content values were higher in LBA cores. This was likely due to the more efficient conversion of cloud liquid water to precipitation in oceanic areas, and the subsequent fallout because the updrafts were not able to hold the raindrops.

3. Particle concentrations from the two projects were similar, which is counter to the idea that continental areas would have higher concentrations of smaller particles. However, other studies have also demonstrated that the environment of LBA was more oceanic in character than continental.
4. The updraft characteristics for LBA and KWAJEX are similar to other tropical studies performed by research aircraft. The tropical updraft values are small in comparison to the midlatitude continental values for speed and mass flux.
5. Remote sensing instruments often show that strong updrafts do not peak until they are at an altitude above where the aircraft were flying.
6. The environmental characteristics were similar during LBA and KWAJEX and compared favorably to other studies, such as EMEX. The main difference was height of the LCL and LFC, which was higher in LBA.
7. Updraft cores during LBA and KWAJEX contained only a small fraction of the adiabatic liquid water content, and achieved only a small fraction of the vertical velocity predicted by parcel theory. This is in line with other studies from tropical areas. Higher fractions of both variables were correlated well with each other.
8. Entrainment and mixing likely played an important role in reducing the amount of vertical velocity in the updrafts from LBA and KWAJEX. Other possible factors include water loading, boundary layer depth, evaporative cooling and convective inhibition.

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